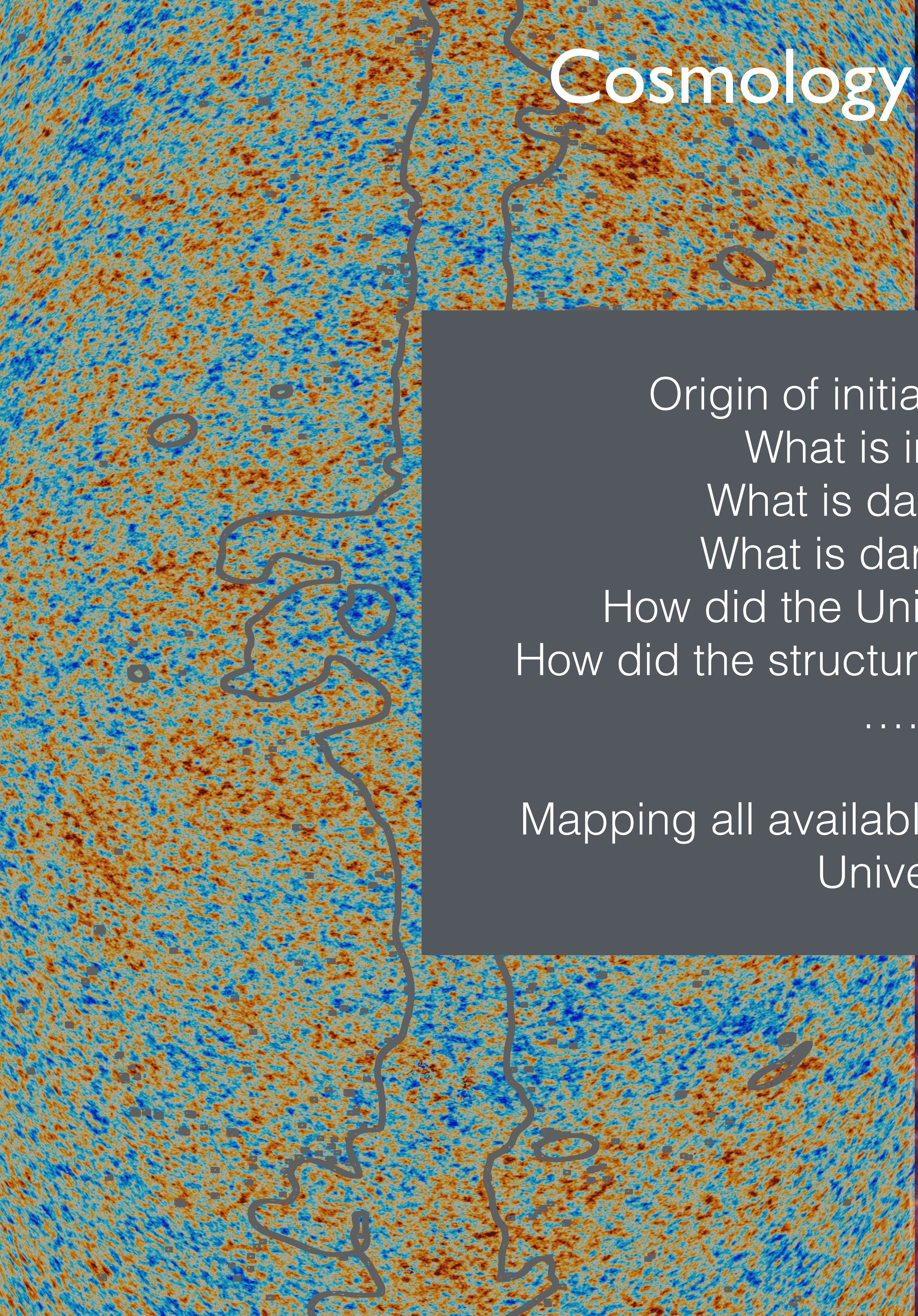
Jet Propulsion Laboratory
California Institute of Technology

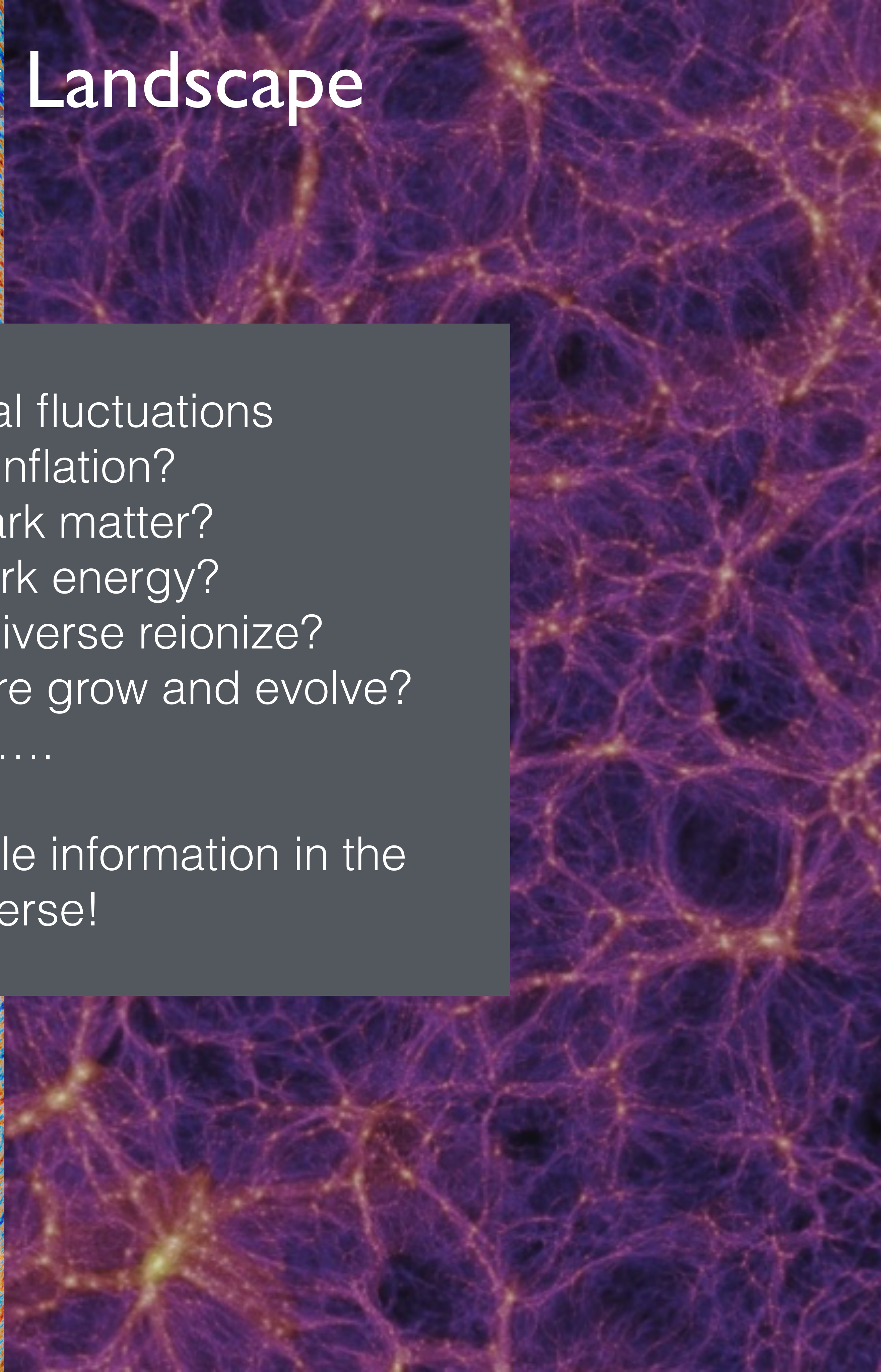
Near-Term Multiple-Line Intensity Mapping

Tzu-Ching Chang

Jet Propulsion Laboratory
California Institute of Technology

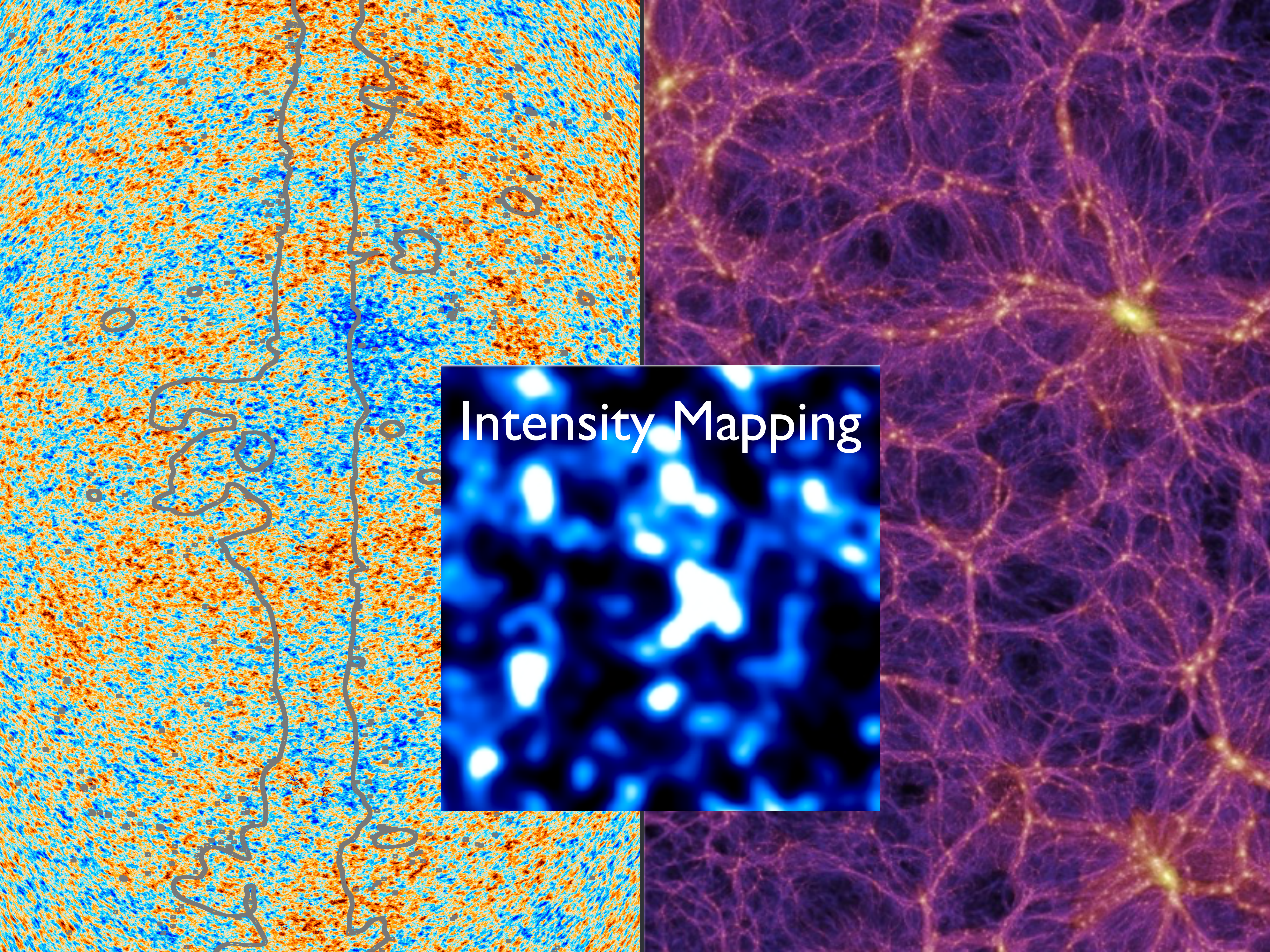
Cosmology Landscape

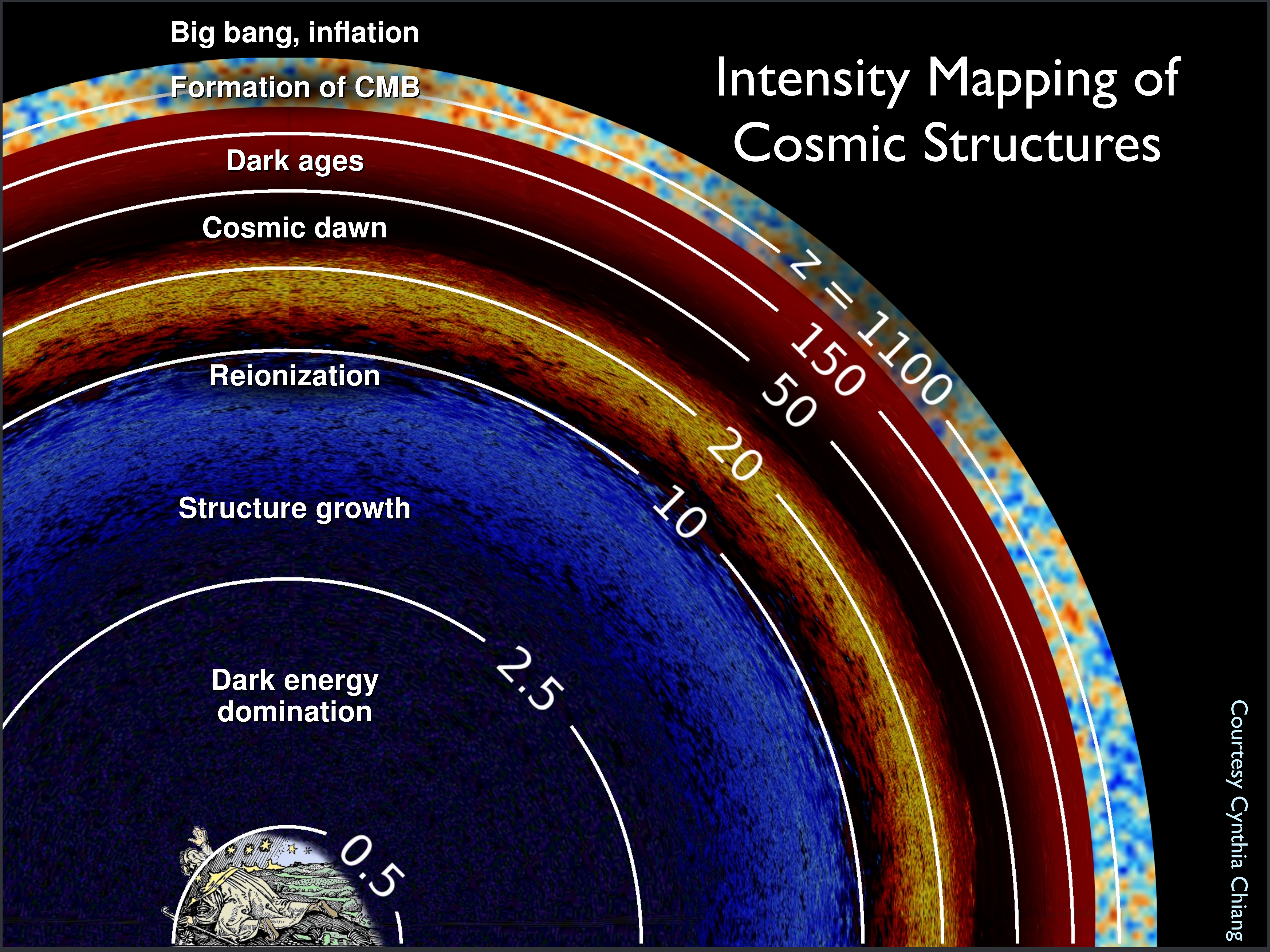


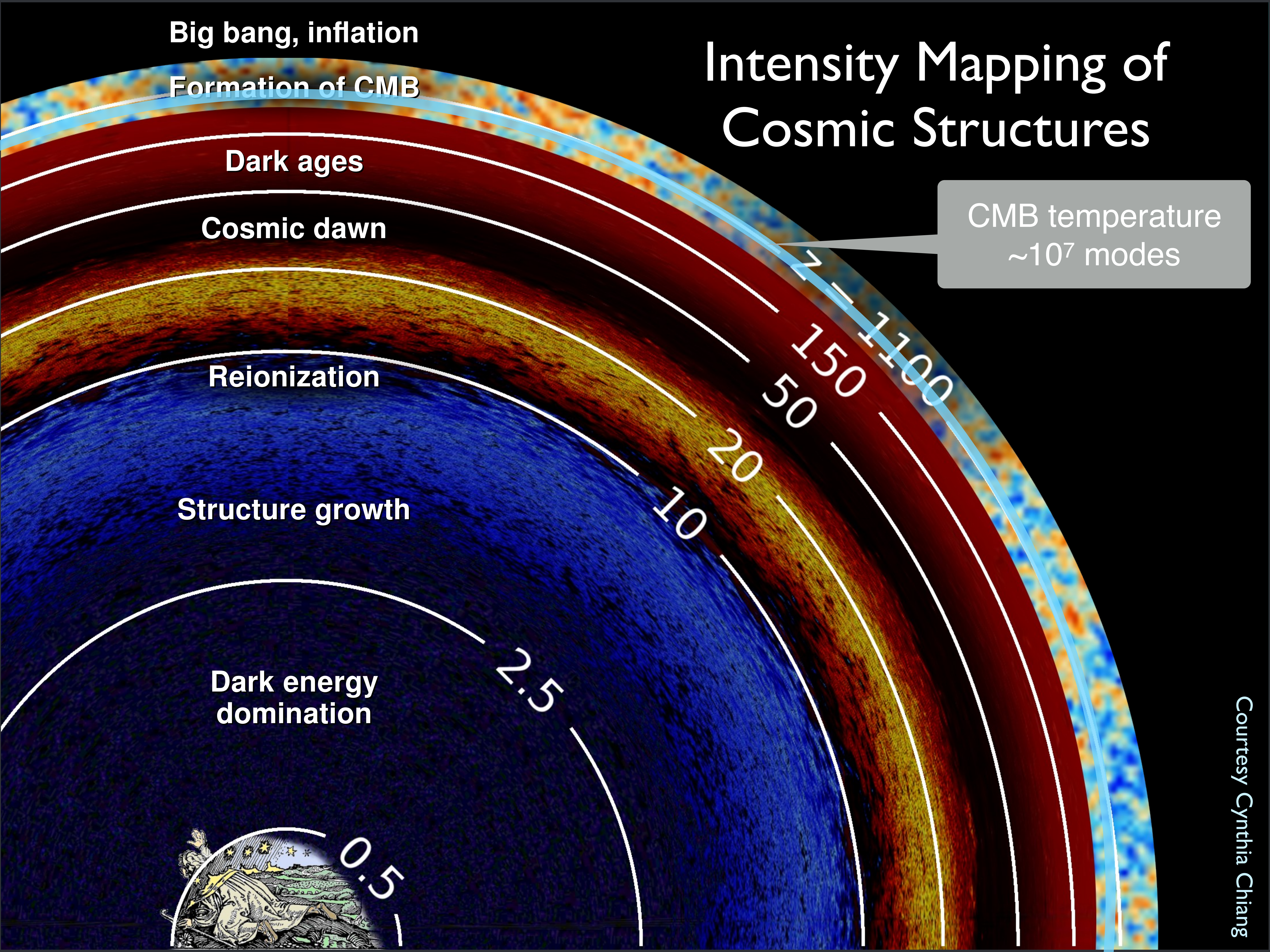


Origin of initial fluctuations
What is inflation?
What is dark matter?
What is dark energy?
How did the Universe reionize?
How did the structure grow and evolve?
…….

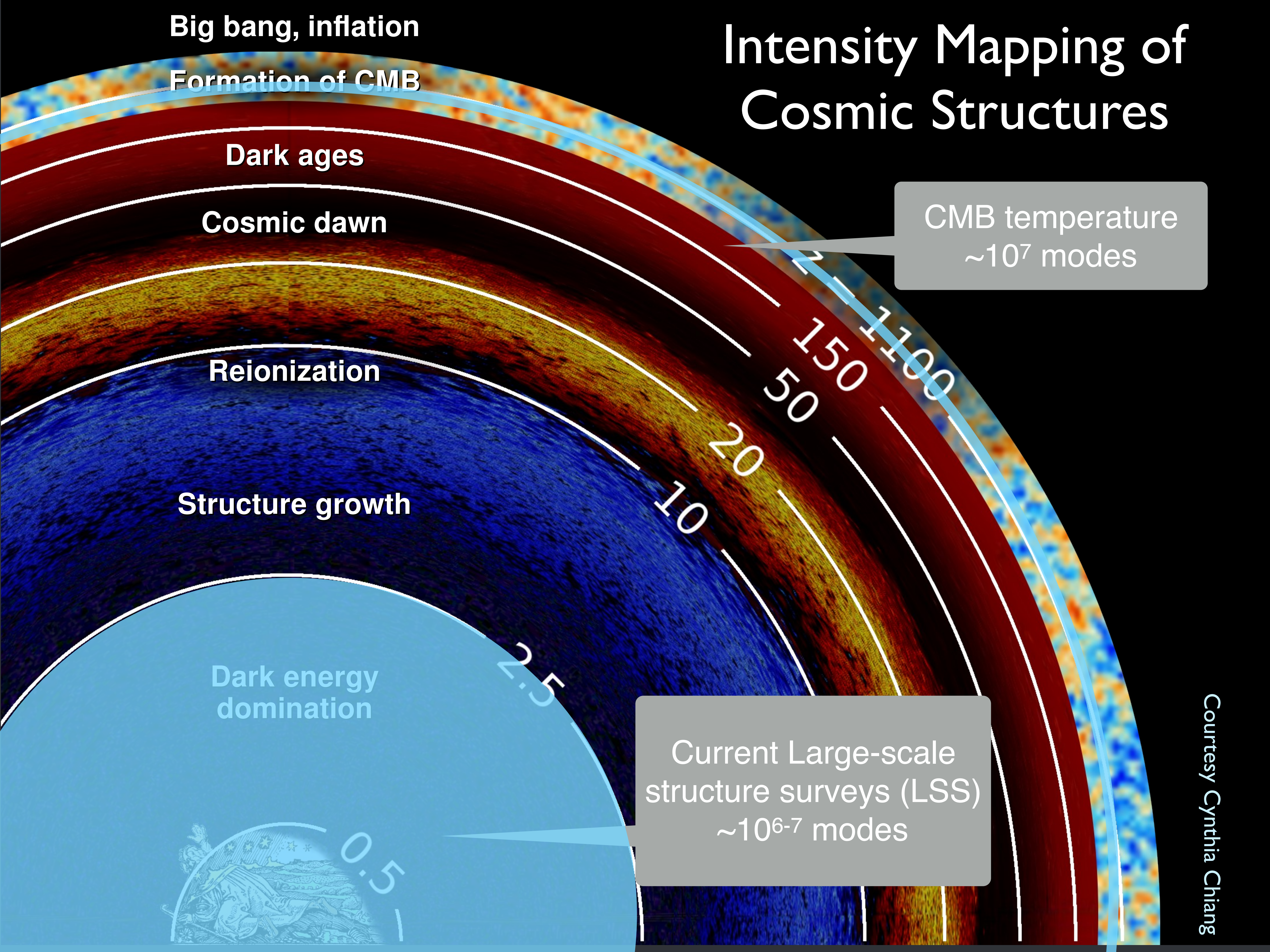
Mapping all available information in the Universe!

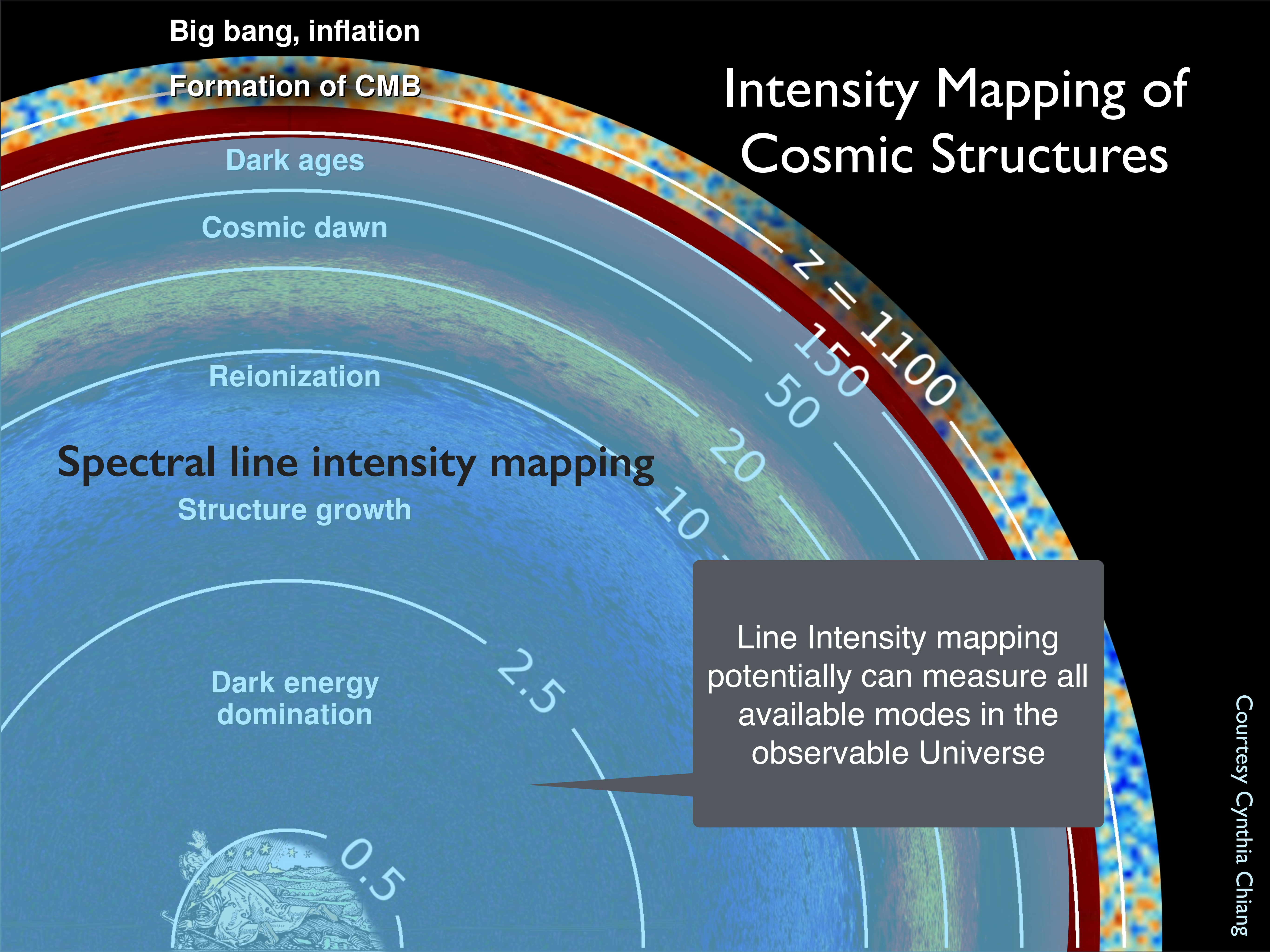

Intensity Mapping


Intensity Mapping of Cosmic Structures
Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5
Courtesy Cynthia Chiang

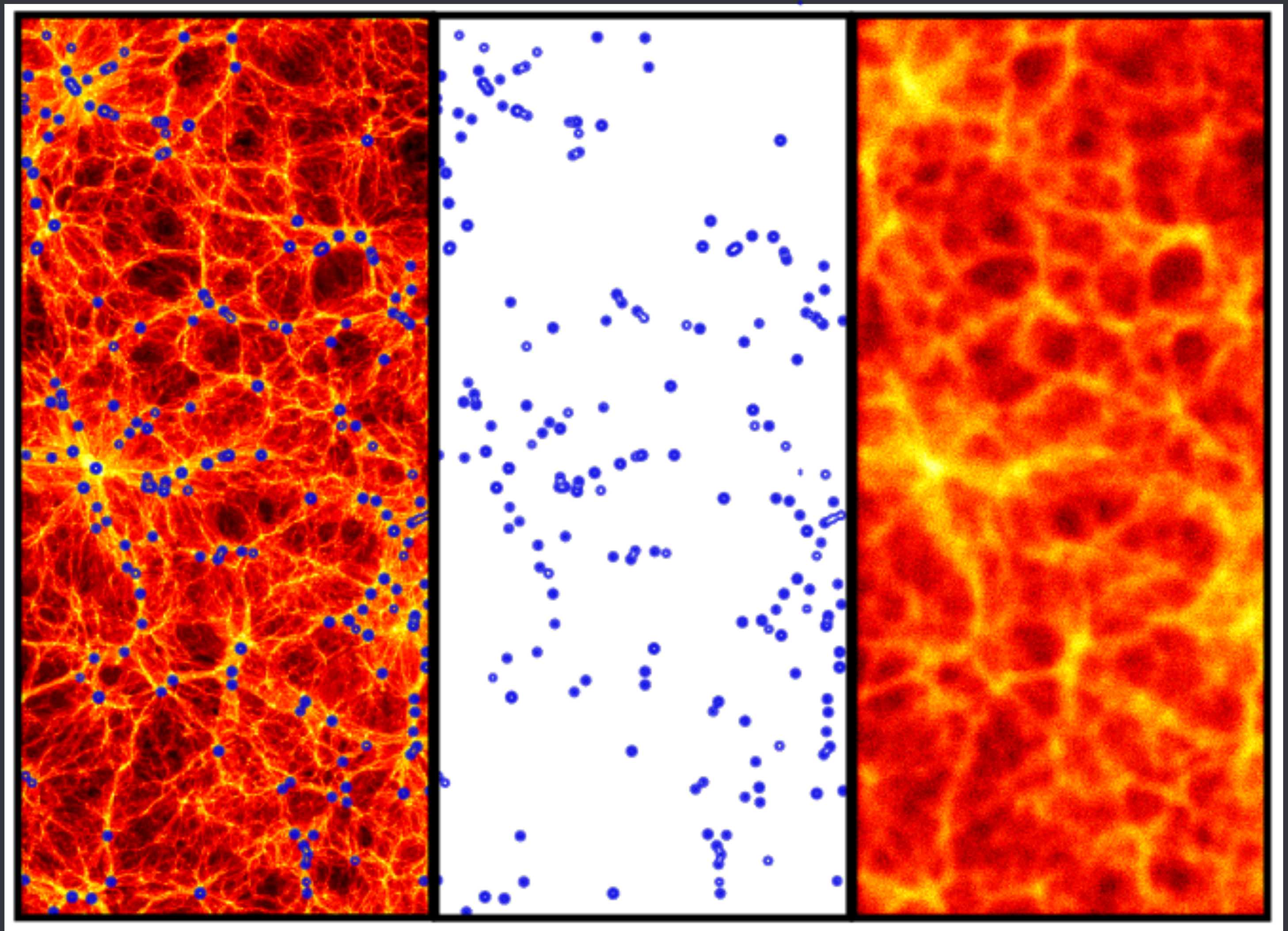

Intensity Mapping of Cosmic Structures
Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
CMB temperature
~10^7 modes
z = 1100
150
50
20
10
2.5
0.5
Courtesy Cynthia Chiang

Intensity Mapping of Cosmic Structures




Intensity Mapping of Cosmic Structures
Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Spectral line intensity mapping
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5
Line Intensity mapping potentially can measure all available modes in the observable Universe
Courtesy Cynthia Chiang

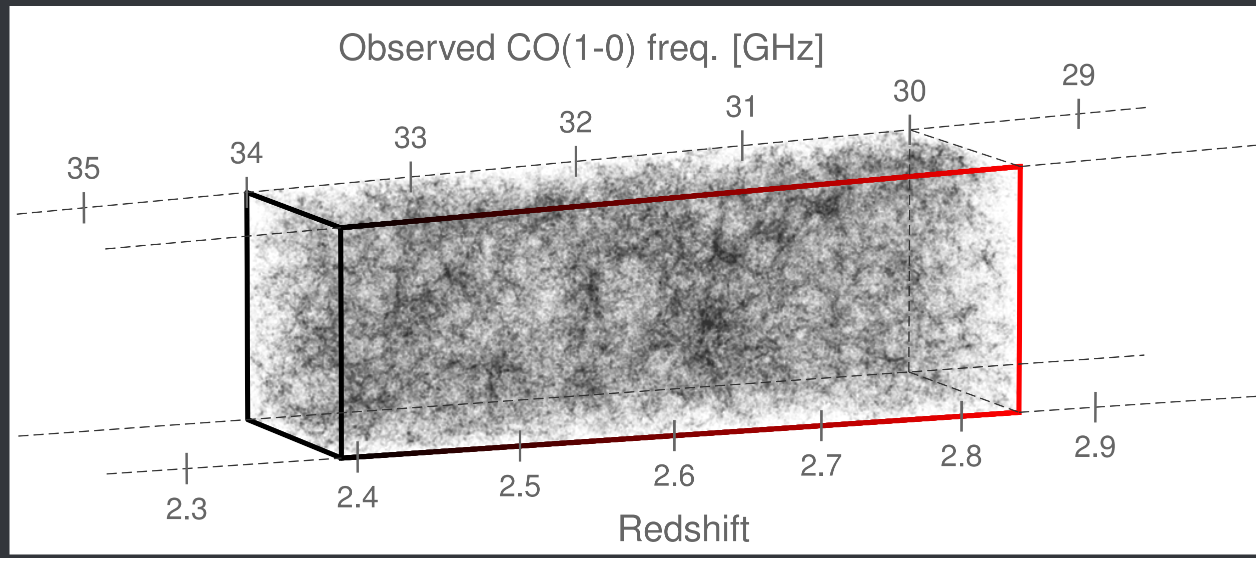
Line Intensity Mapping (IM)



courtesy Phil Korngut

- "Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008):
  - Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain high frequency resolution thus redshift information
- Measure brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: economical, large survey volumes
- Confusion-limited. Foreground-limited.

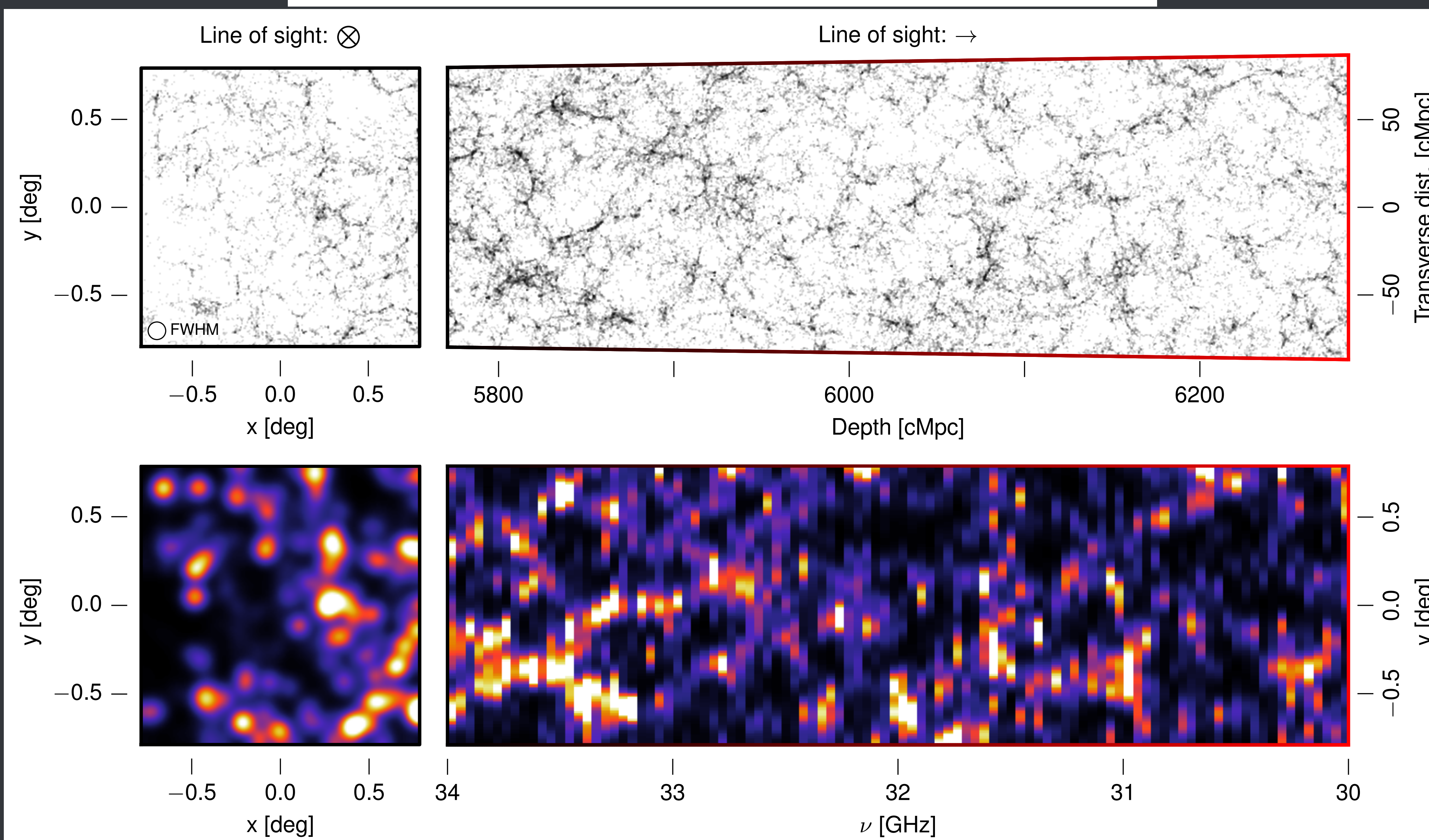
Intensity Mapping Sciences



A tracer of the 3D large-scale cosmic structures:

Luminosity-weighted density field

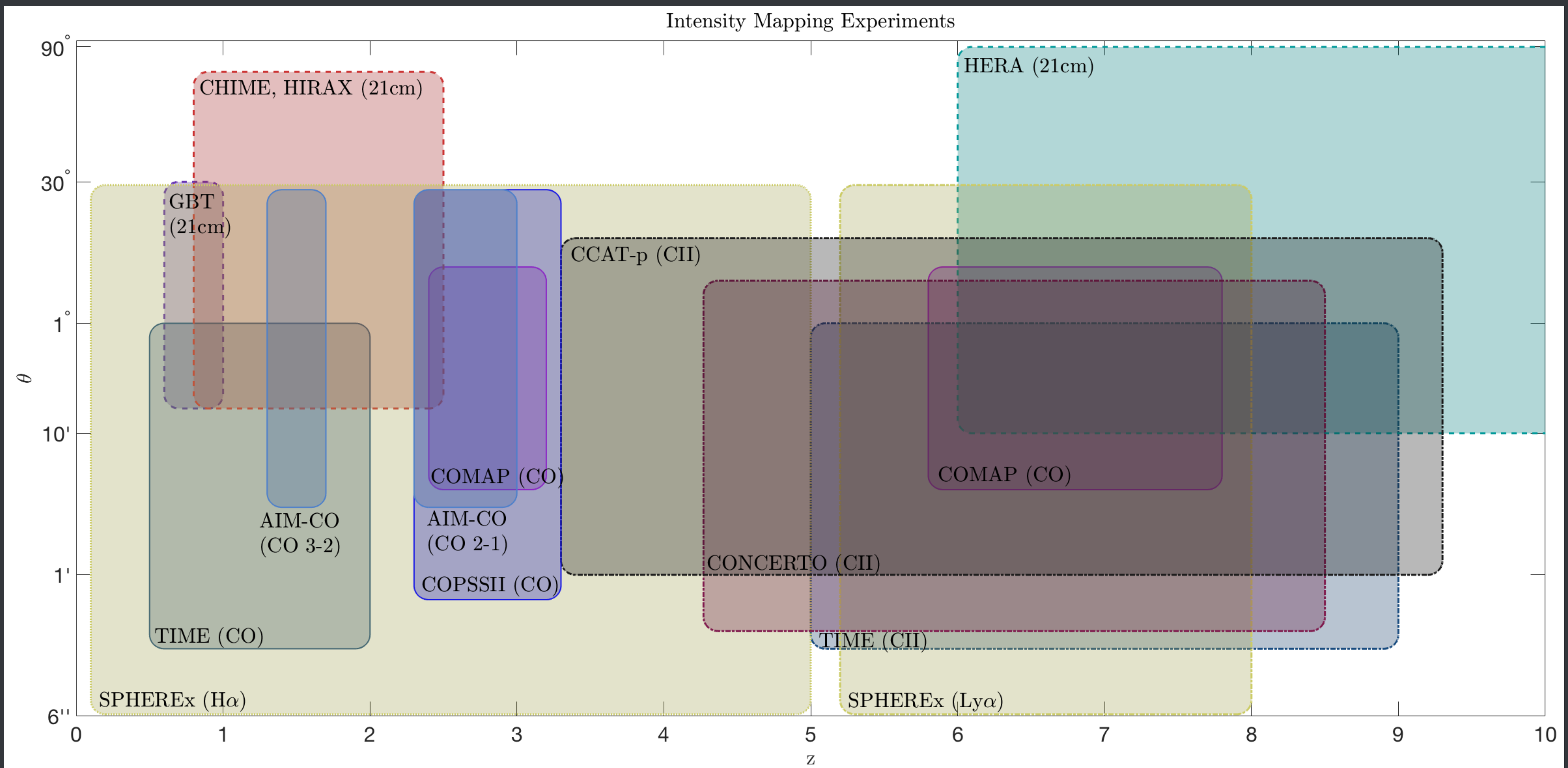
Li+16



Astrophysics: L(M)
Cosmology: $P_L(k, z)$

Brightness temperature fluctuations $dT(\theta, \nu)$

(21cm, CO, [CII], Lya, Ha) Intensity Mapping Experiments

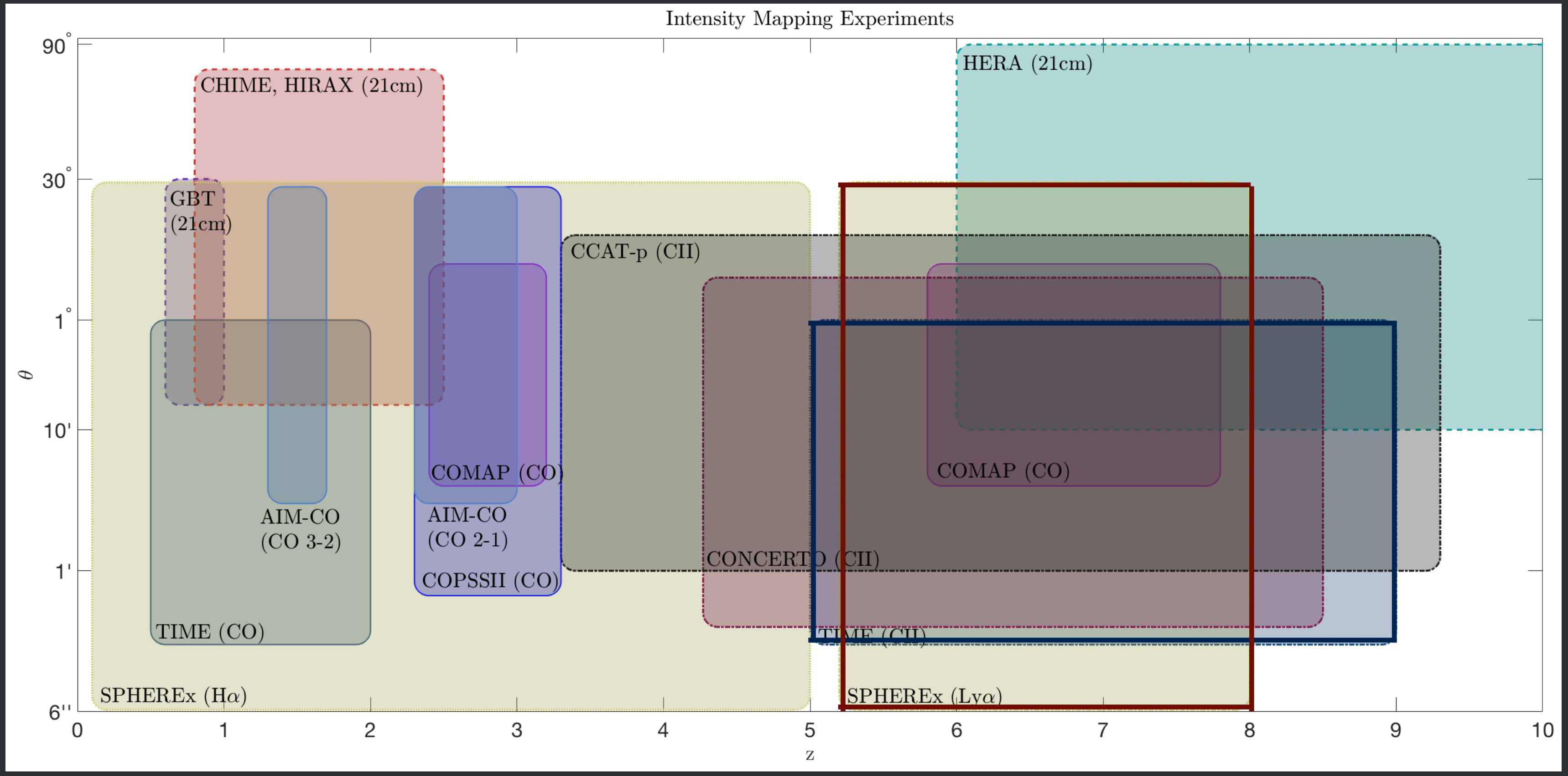


θ

z

Intensity Mapping status report (Kovetz+ 2018)

IM: a representative view of the Universe



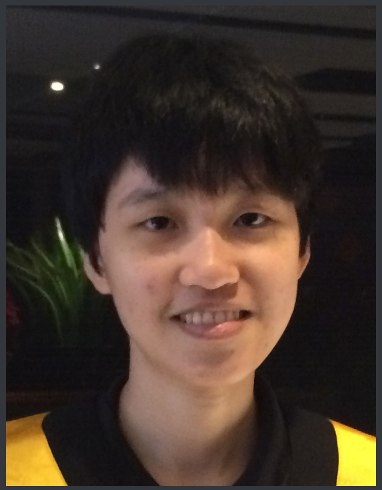
Peak of Star formation

Cosmic reionization

z

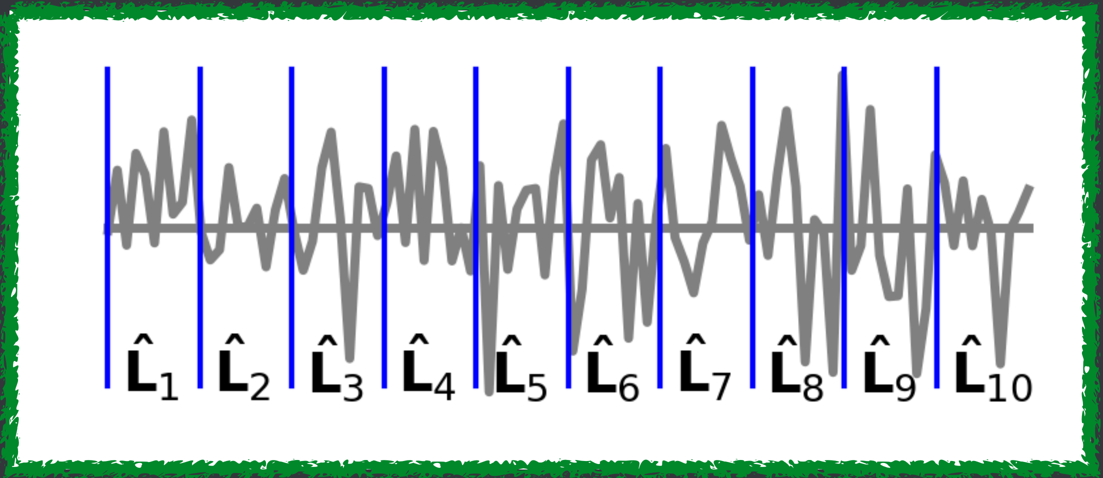
Dark energy domination

Cosmic Dawn

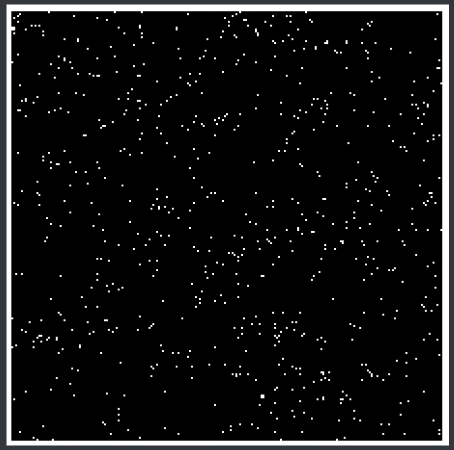


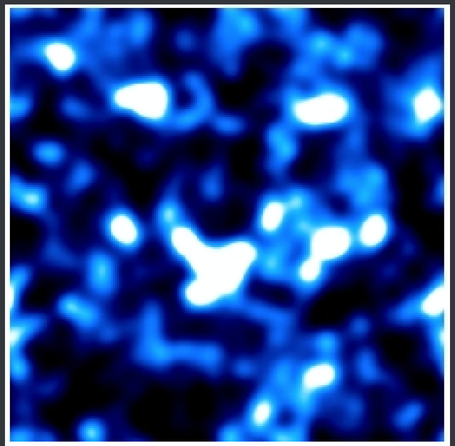
IM vs. Spectro. Galaxy Surveys

w/ Yun-Ting Cheng (Caltech), Roland de Putter, O. Doré



- Goal: map out the 3D large-scale structure by measuring the voxel luminosity *L* of a tracer in a 3D volume.
- Density field, δ, is traced by observable *O(L)*.





- Spectro. galaxy survey: *O(L)* a step function.
  - *O(L)=1*, if $L > L_{th}$,
  - *O(L)=0*, otherwise. A digitized 3D map.
- IM: include all photons. *O(L)=L*. A continuous 3D map.

IM vs. Spectro. Galaxy Surveys
A Toy Model

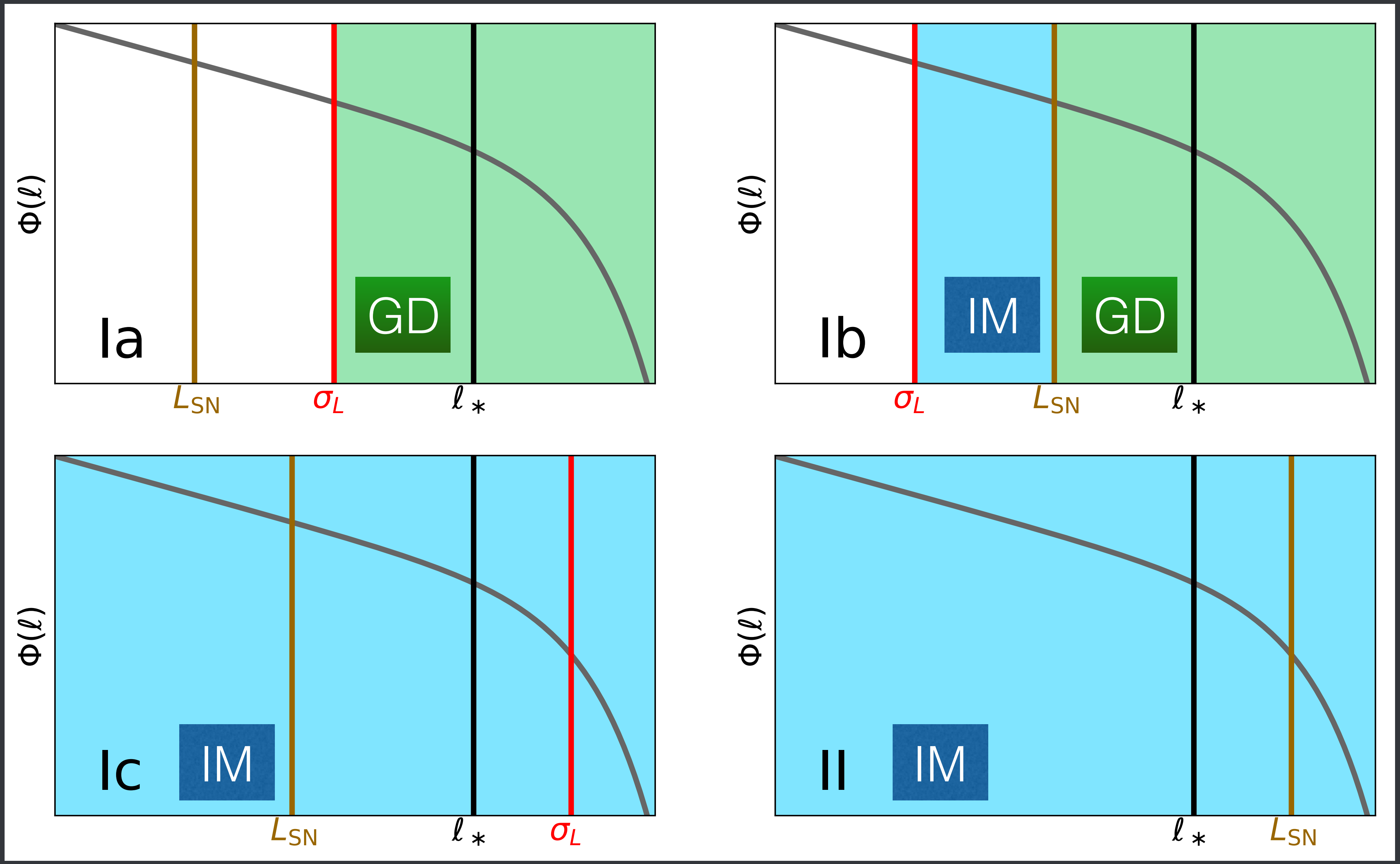
- Question: Given a tracer luminosity function $\Phi(l, \delta)$, what is the optimal observable, $O_{opt}(L)$?

- Tool: Use *P(D)* — the voxel luminosity PDF in density field δ, $P(L, \delta)$, to derive $O_{opt}(L)$.

- Parameters:
  - *Signal:* tracer luminosity function, $\Phi(l, \delta)$, *assume a Schechter func* $\rightarrow \ell_*$
  - *Noise:* assume Gaussian thermal noise $\rightarrow \sigma(L)$
  - *Confusion noise:* *shot noise from fainter sources* $\rightarrow L_{SN}$

- Optimal Observable:
  - $\mathcal{O}^{\rm opt}(L) = \partial_\delta \ln \mathrm{P}(\mathrm{L}, \delta)$
  - *Calculate information context for IM and GD*

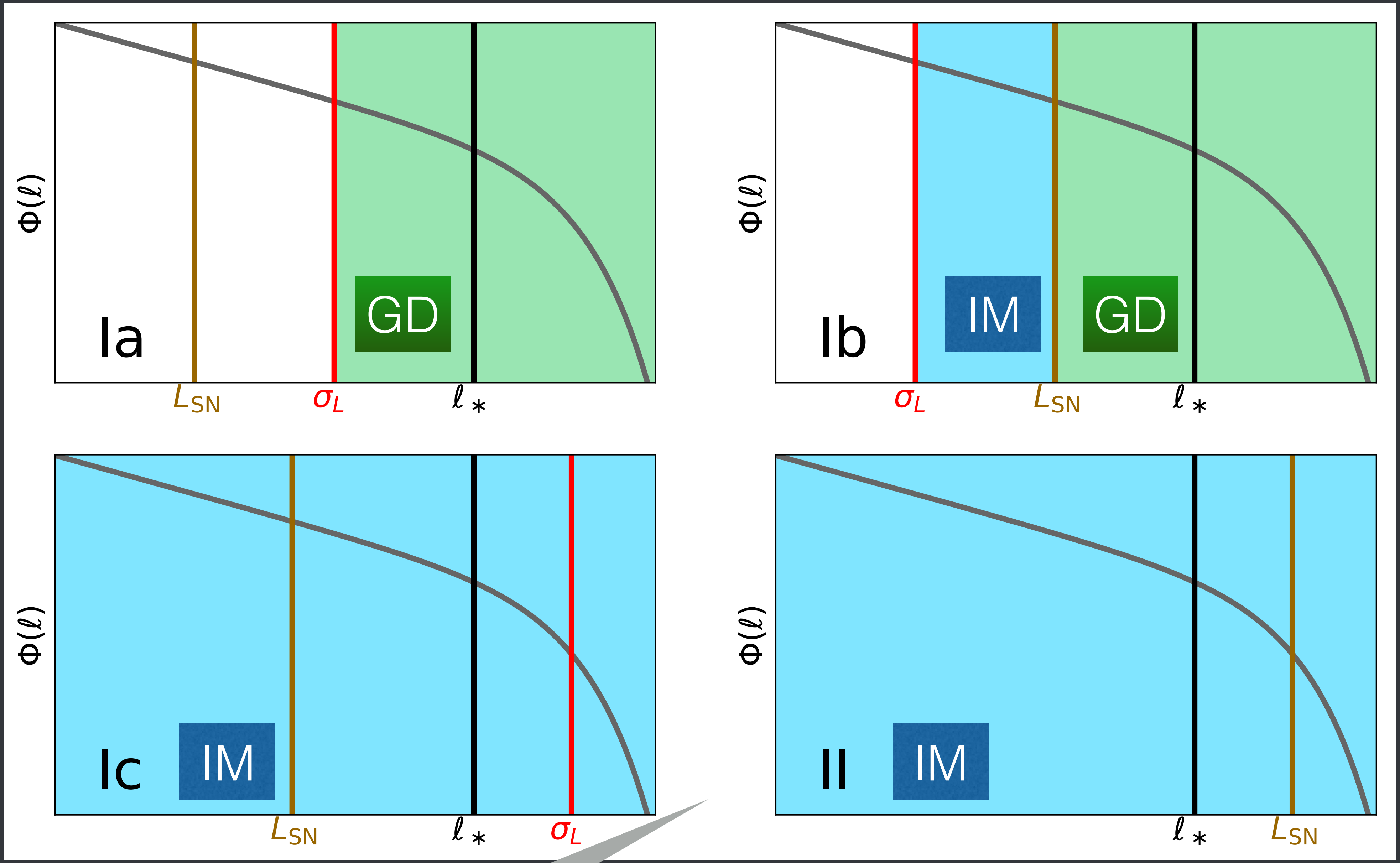
Intensity Mapping (IM) vs. Galaxy Detection (GD)



Cheng et al., 2018

ℓ_* – characteristic source luminosity
σ_L – instrument noise
L_{SN} – confusion scale

IM vs. Spectro. Galaxy Surveys



Cheng et al., 2018

21cm
Intensity Mapping

ℓ_* – characteristic source luminosity
σ_L – instrument noise
$L_{\rm SN}$ – confusion scale

TIME in a nutshell

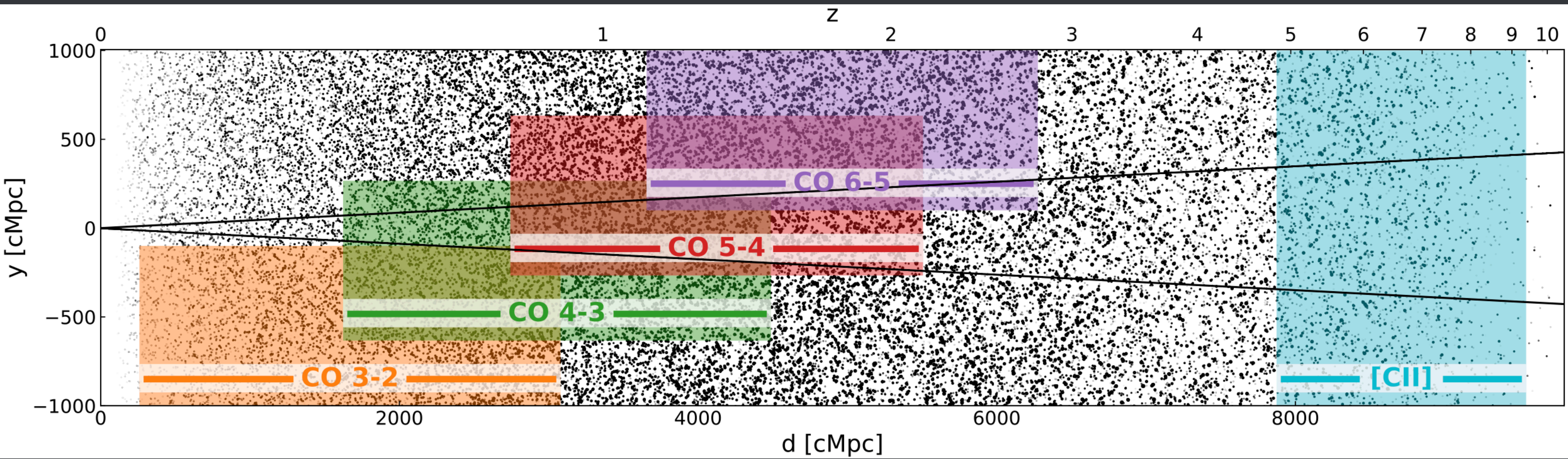
- A [CII] Intensity Mapper for EoR at $5.3 < z < 8.5$
  - Covering 195-295 GHz at R~100 (183-326 GHz including atmosphere monitoring channels)
  - 32 grating spectrometers (2 polarizations)
  - 1920 TES bolometer detectors
  - 16 spatial pixels and 60 spectral channels
  - FoV: 11 arcmin x 0.4 arcmin
  - Nominal survey: ~1 deg x 0.4 arcmin
  - Engineering run now: Jan-March 2019
  - 1000 hours of winter observing time at the Kitt Peak ALMA 12-m Prototype Antenna, starting winter 2019

TIME in a nutshell

TIME Collaboration

Abigail Crites, Jamie Bock, Matt Bradford, Tzu-Ching Chang, Yun-Ting Cheng, Steve Halley-Dunsheath,
Ben Hoscheit, Jonathan Hunacek, Lorenzo Moncelsi, Roger O'Brient, Guochao Jason Sun (Caltech/JPL)
Chao-Te Li, Da-Shun Wei (ASIAA), Victoria Butler, Mike Zemcov (RIT)
Ryan Keenan, Dan Marrone, Issac Trumper (Arizona), Bade Uzgil (NRAO), Asantha Cooray (UCI)

TIME Lightcone

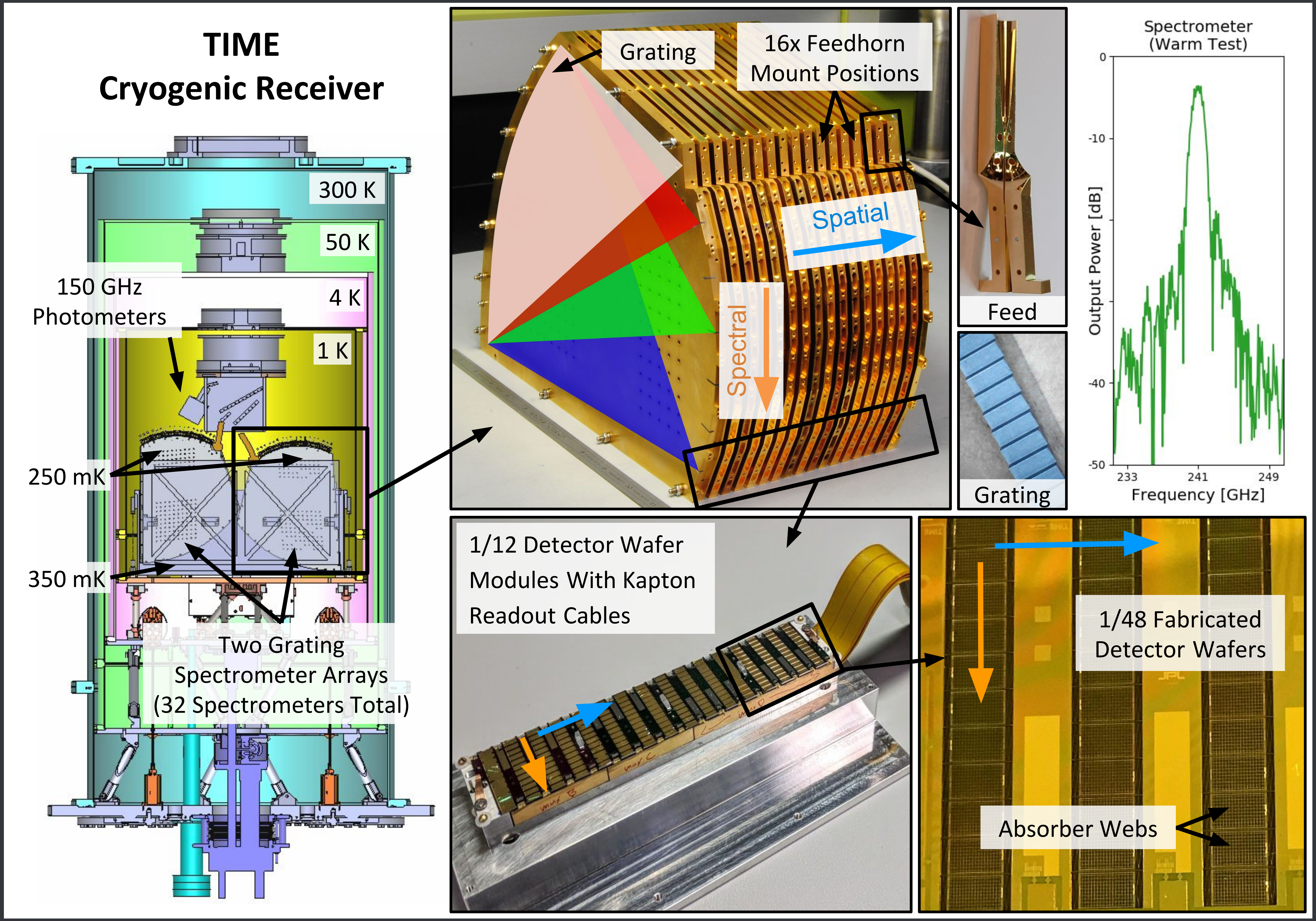


TIME collaboration

TIME traces the 3D large-scale cosmic structures via [CII] and CO and measures the luminosity-weighted density field

Astrophysics: L(M)
Cosmology: $P_L(k, z)$

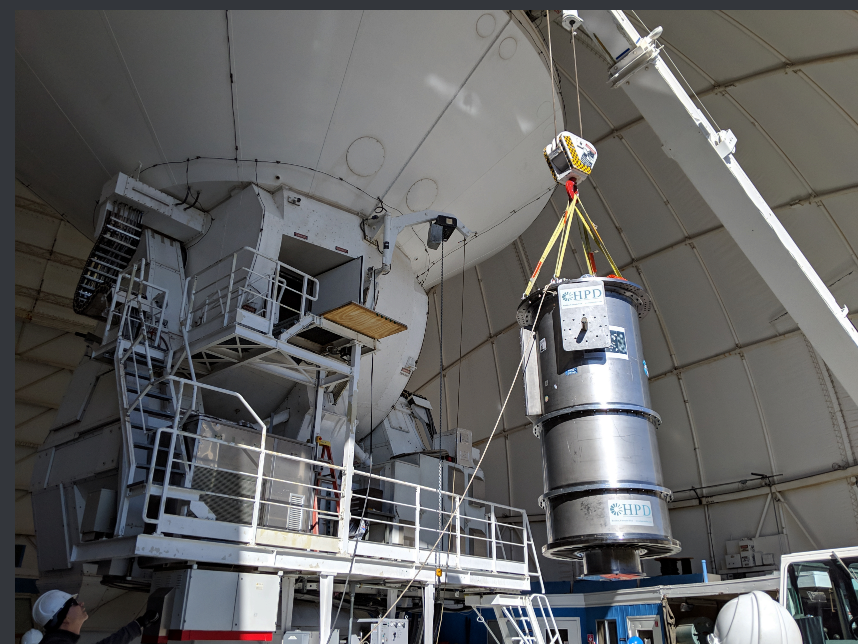
TIME Instrument



TIME collaboration

TIME engineering run @APA

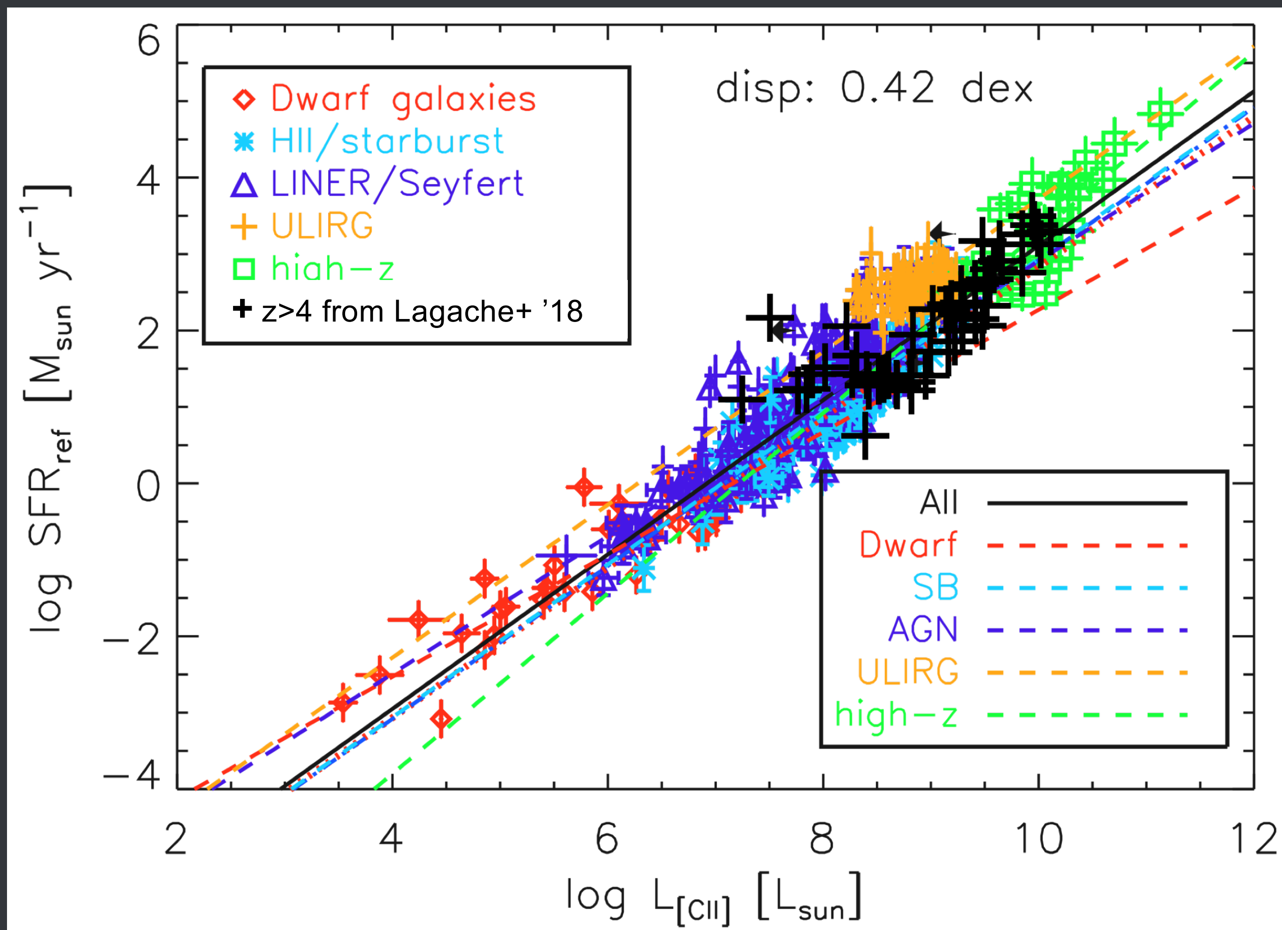
TIME on APA!

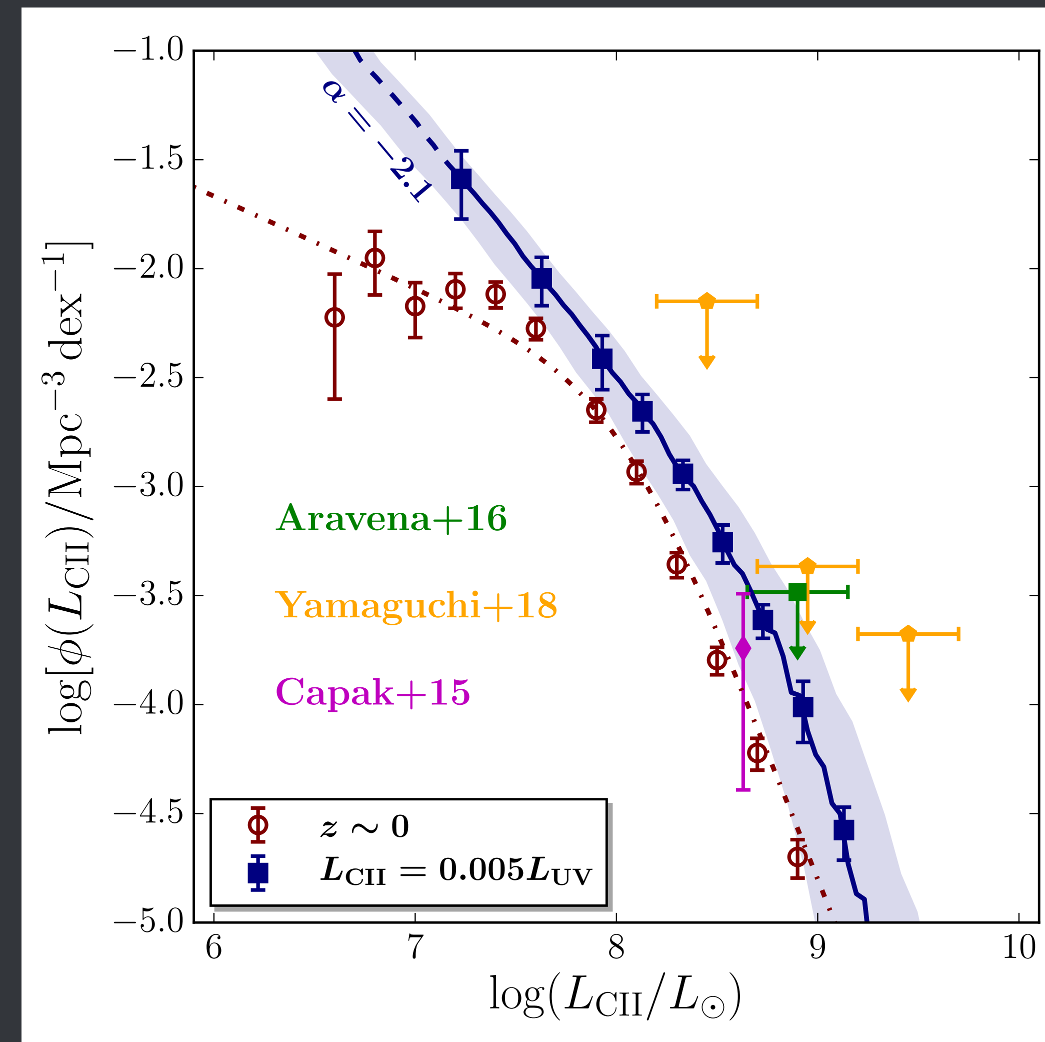


Courtesy Jonathan Hunacek

[CII] at high-z



De Looze et al. 2014

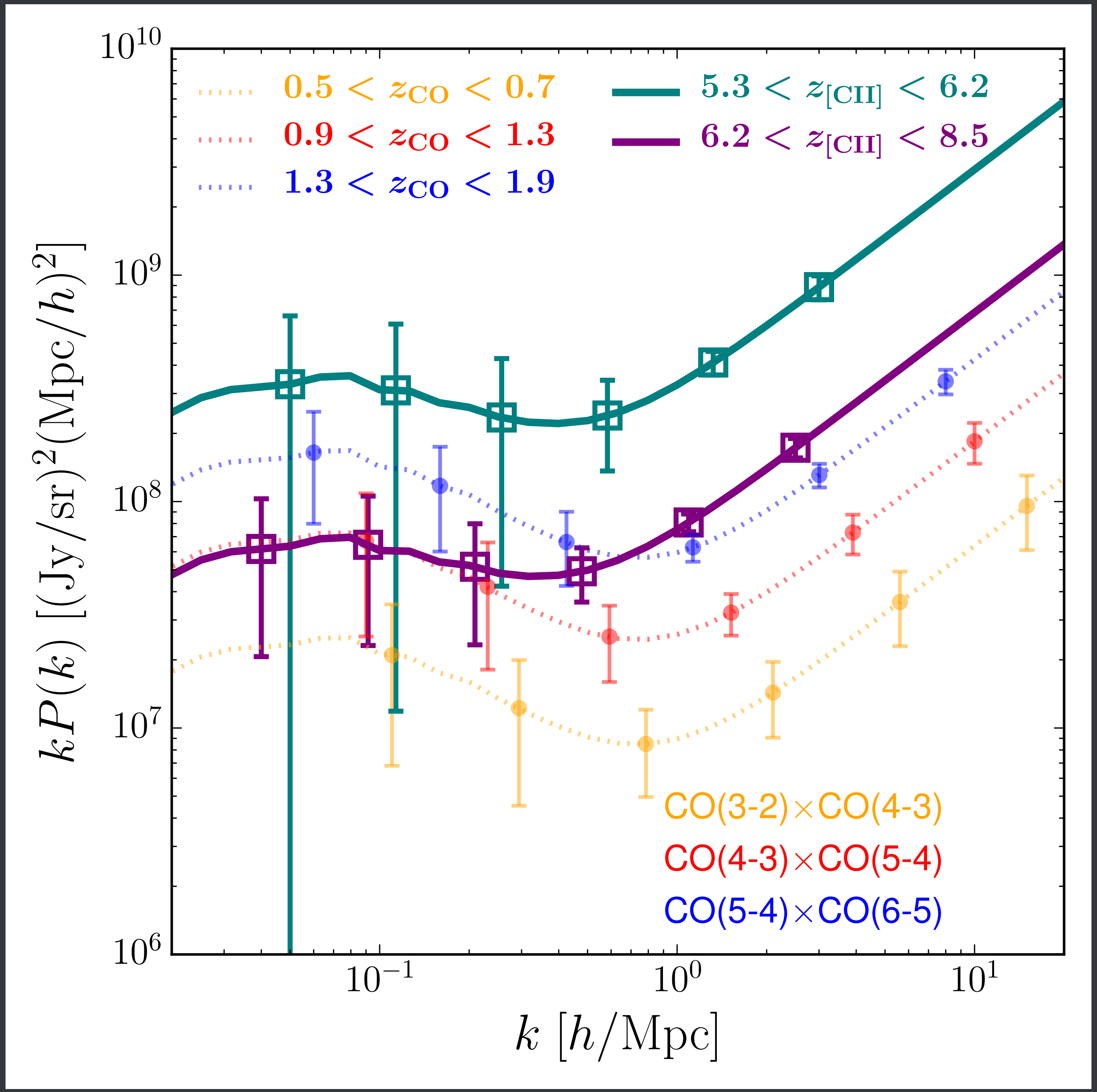


TIME collaboration

- [CII] is a major coolant in ISM, a tracer of Star formation activities.
- $L_{[CII]}/L_{FIR}$ appears to be ~0.001 - 0.01 at high-z from recent ALMA observations (Aravena et al. 2016, Capak et al. 2015)
- ALMA starts to constrain $10^{8.5\text{-}9}$ L_{sun} systems (Aravena et al. 2016, Hayatsu+17)

TIME forecast:

[CII], CO Power Spectra

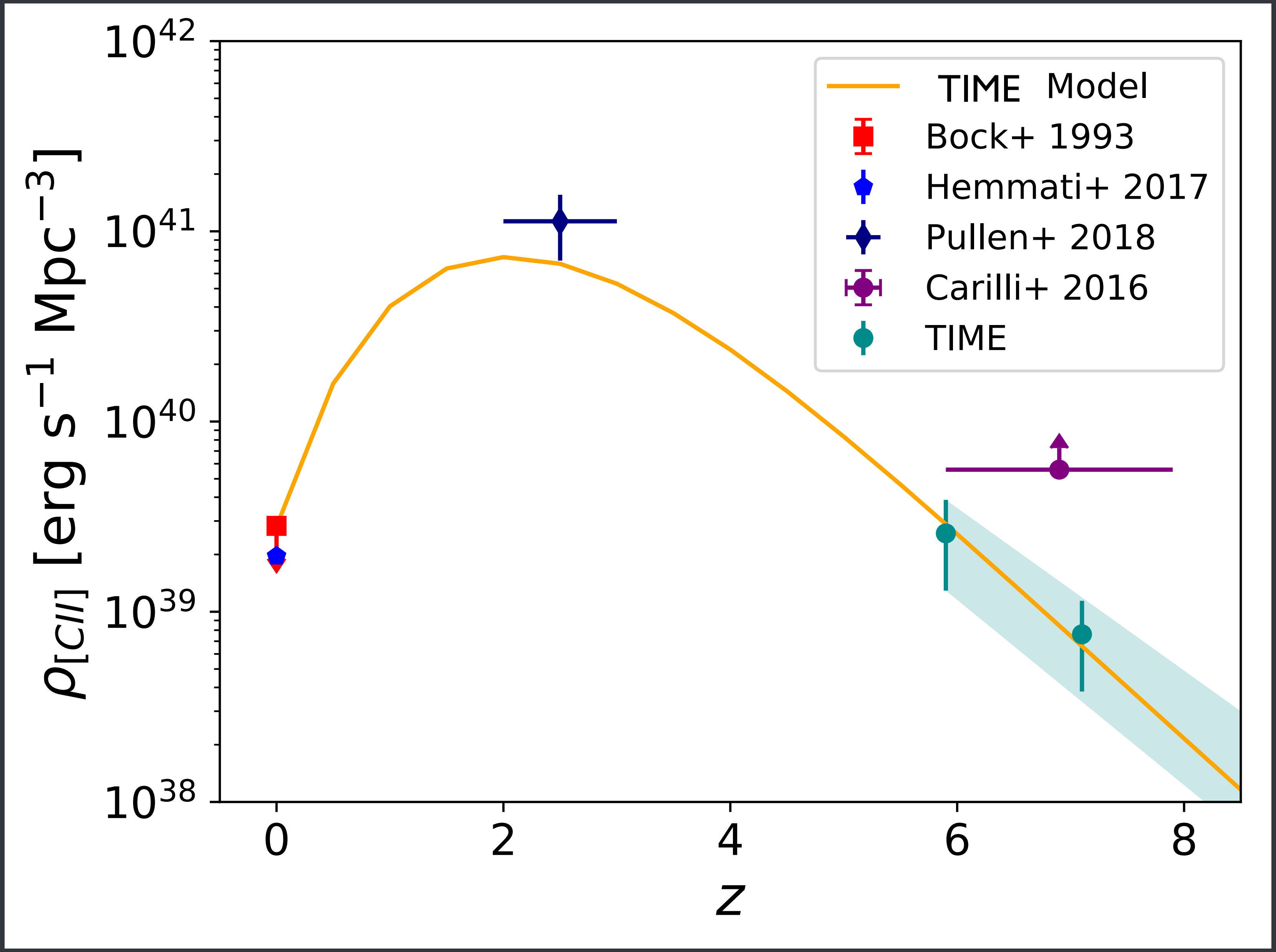


TIME collaboration (Sun et al., in prep)

- [CII]/CO intensity mapping constrains the integral of luminosity function via clustering and shot-noise power spectrum
- Power spectra SNR ~ 10, including estimated signal reduction due to observing strategy, survey geometry, atmospheric and continuum contaminations.

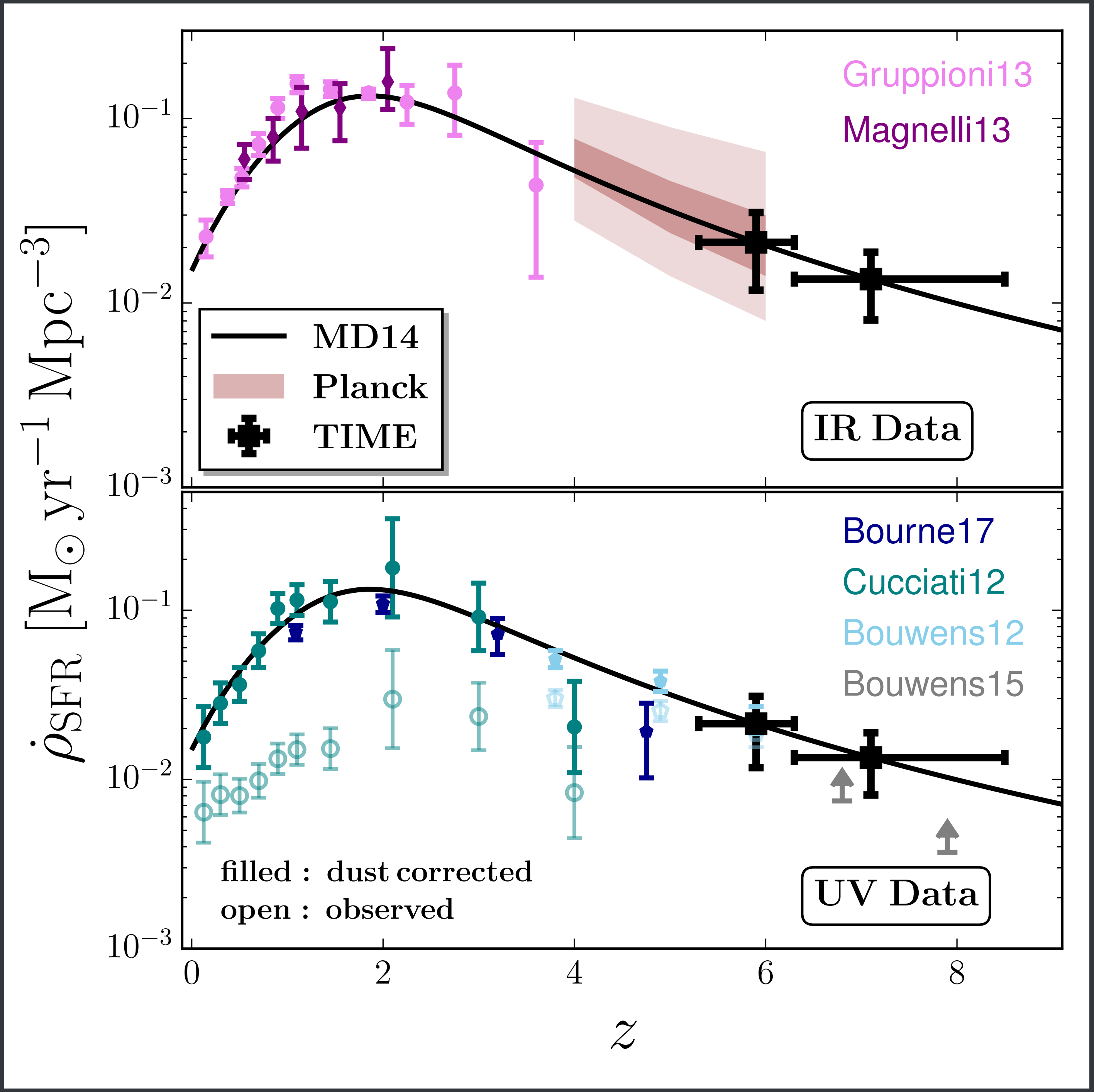
TIME forecast:

Cosmic [CII] abundance



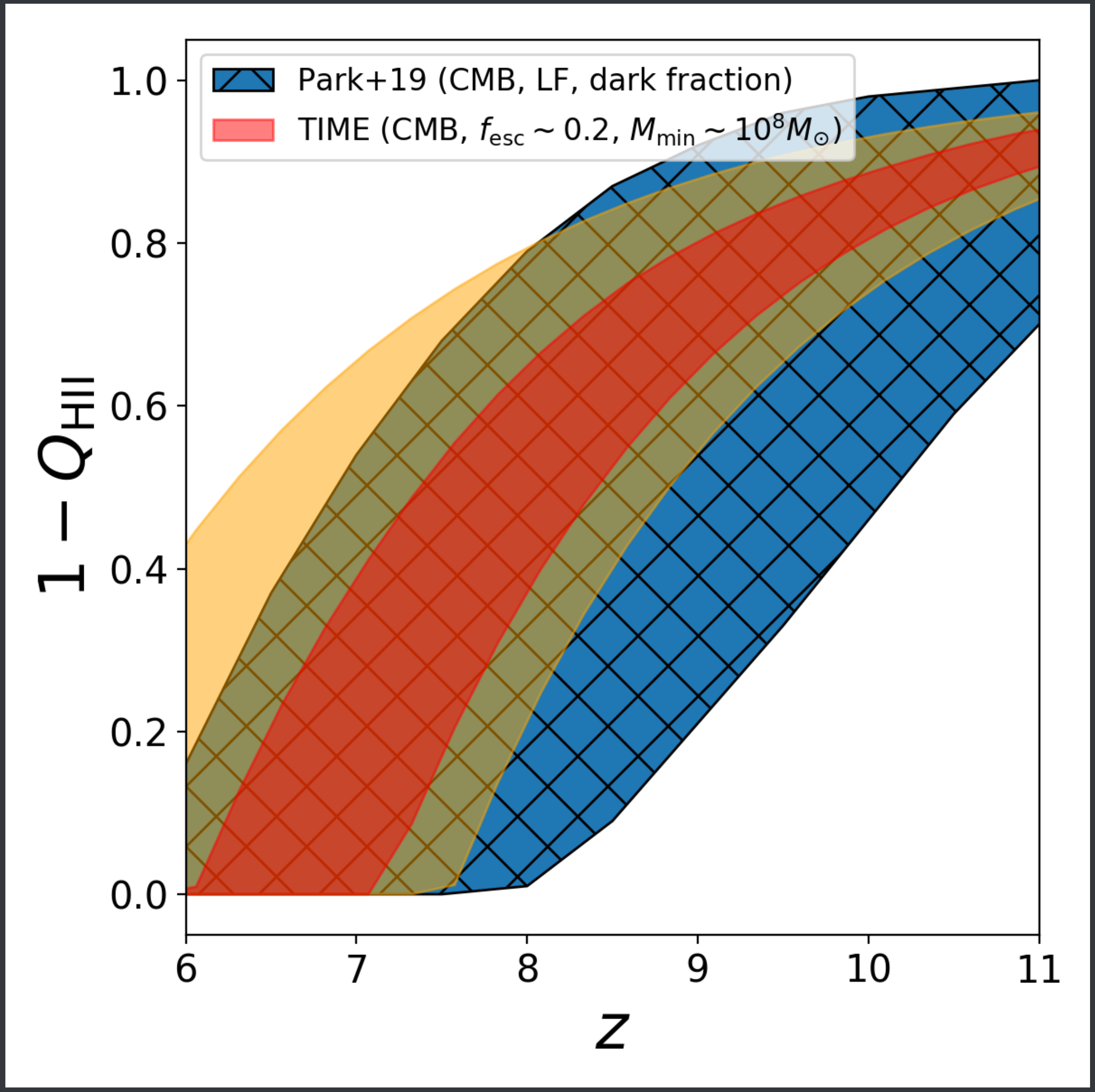
TIME collaboration (Sun et al., in prep)

TIME forecast: SFR constraints at high-z



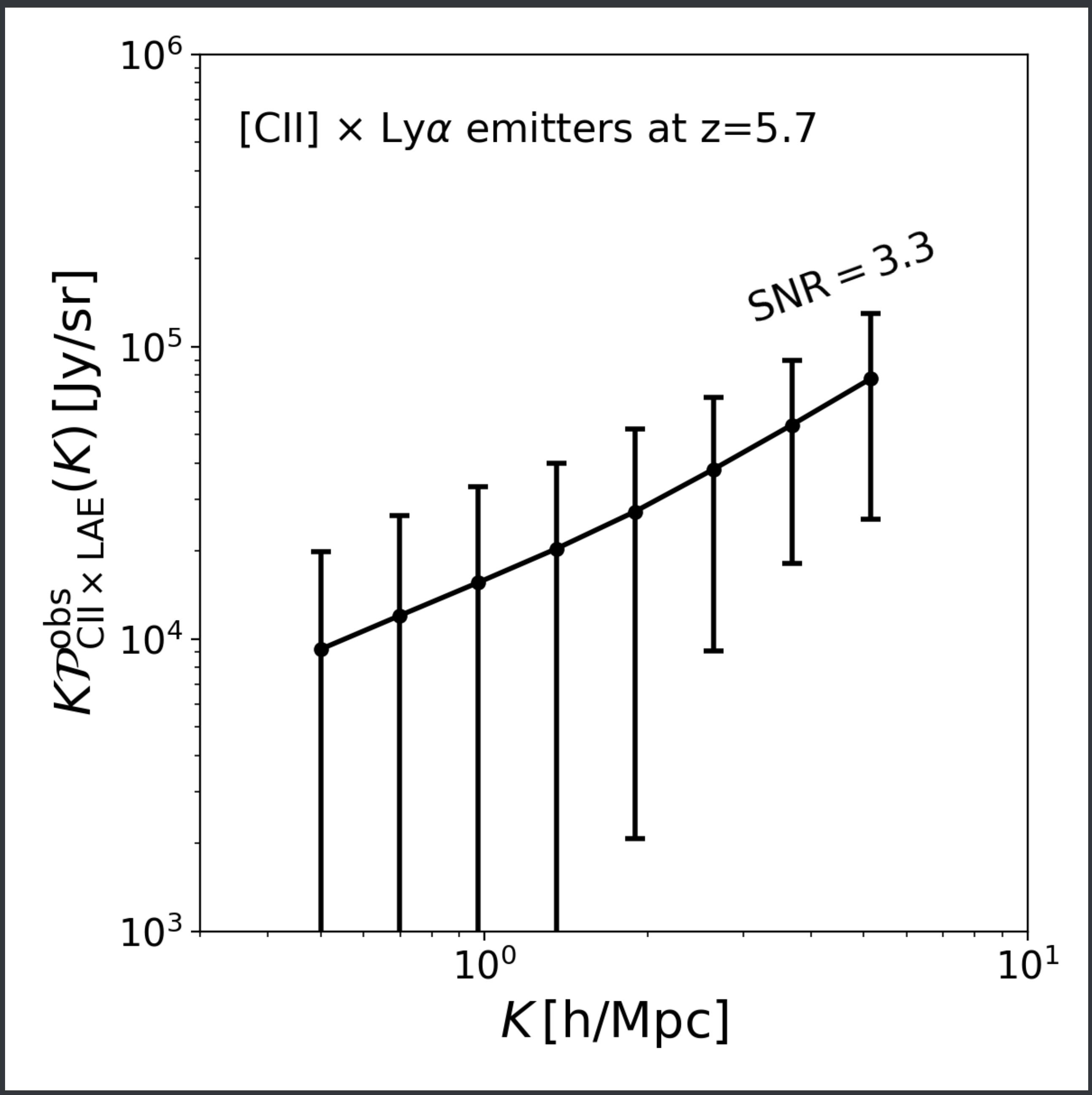
TIME collaboration (Sun et al., in prep)

TIME forecast: Reionization history



TIME collaboration (Sun et al., in prep)

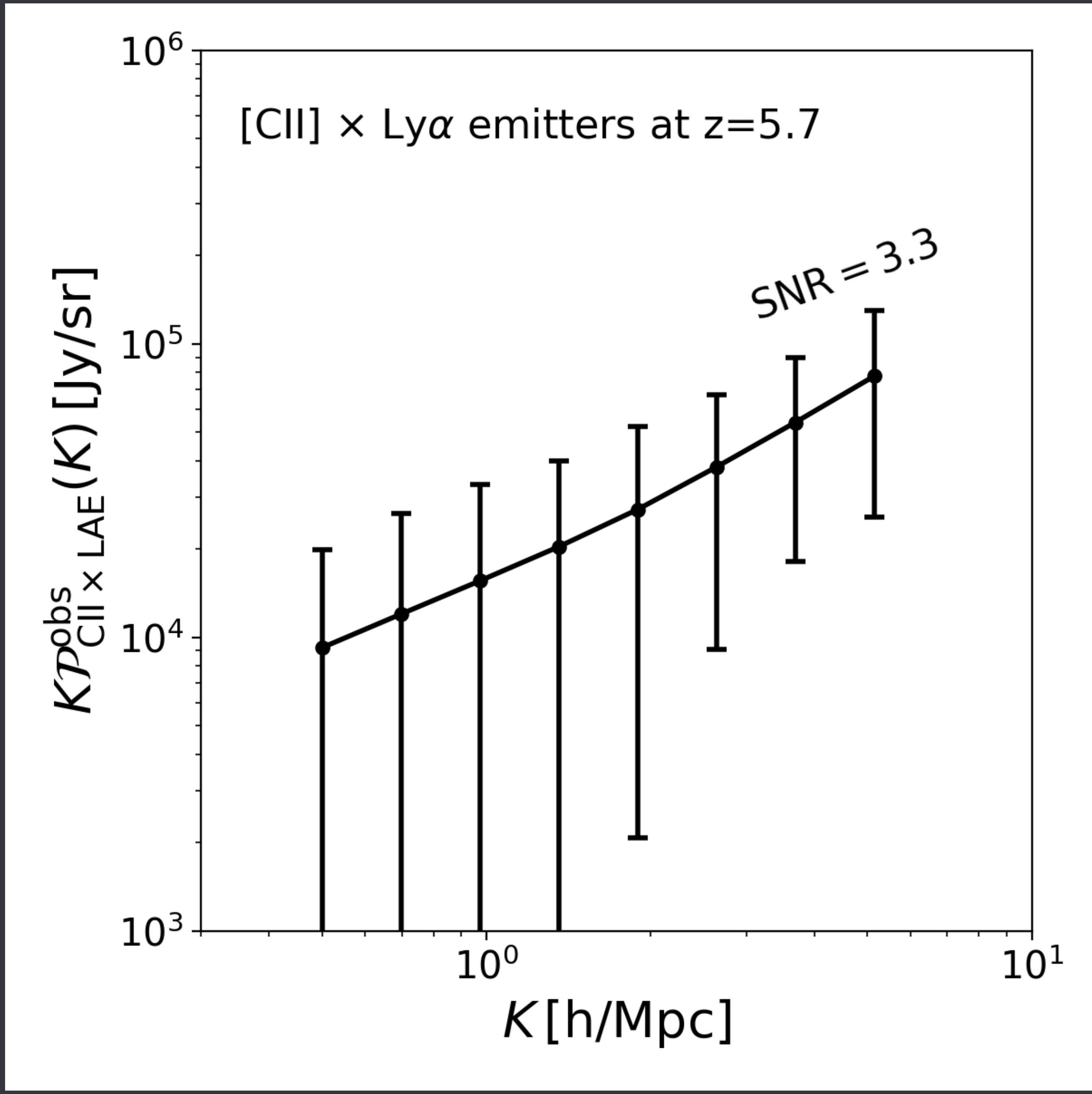
TIME forecast: [CII] x LAE cross correlation



TIME collaboration (Sun et al., in prep)

- [CII] x LAEs from the HSC SILVERRUSH survey at z=5.7
- Currently optimizing the survey depth and geometry for CO, [CII] and [CII]xLAE power spectra

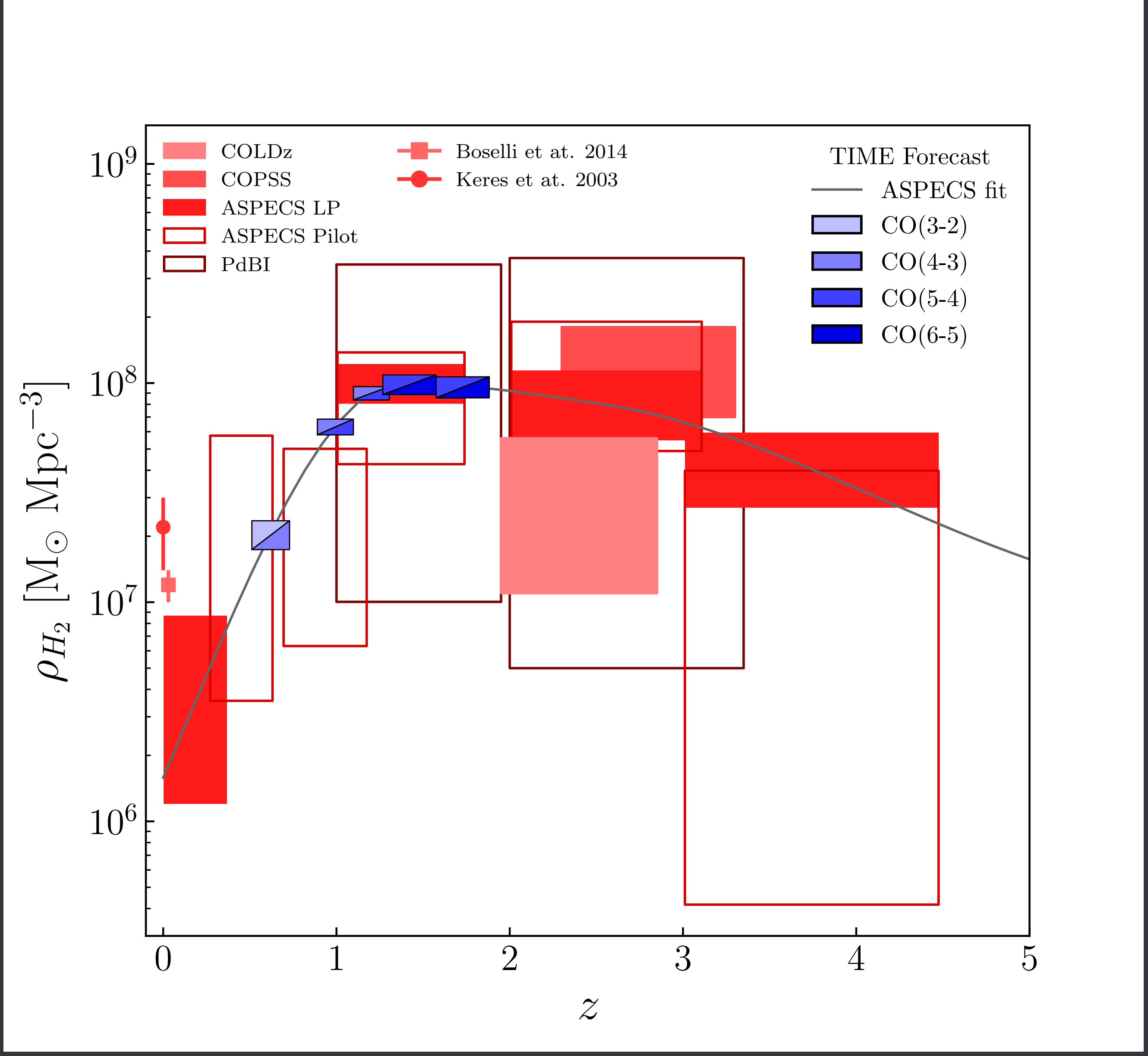
TIME forecast: [CII] x LAE cross correlation



TIME collaboration (Sun et al., in prep)

- [CII] x LAEs from the HSC SILVERRUSH survey at z=5.7
- Currently optimizing the survey depth and geometry for CO, [CII] and [CII]xLAE power spectra

TIME forecast: CO/H_2 abundance at z=0.5-2



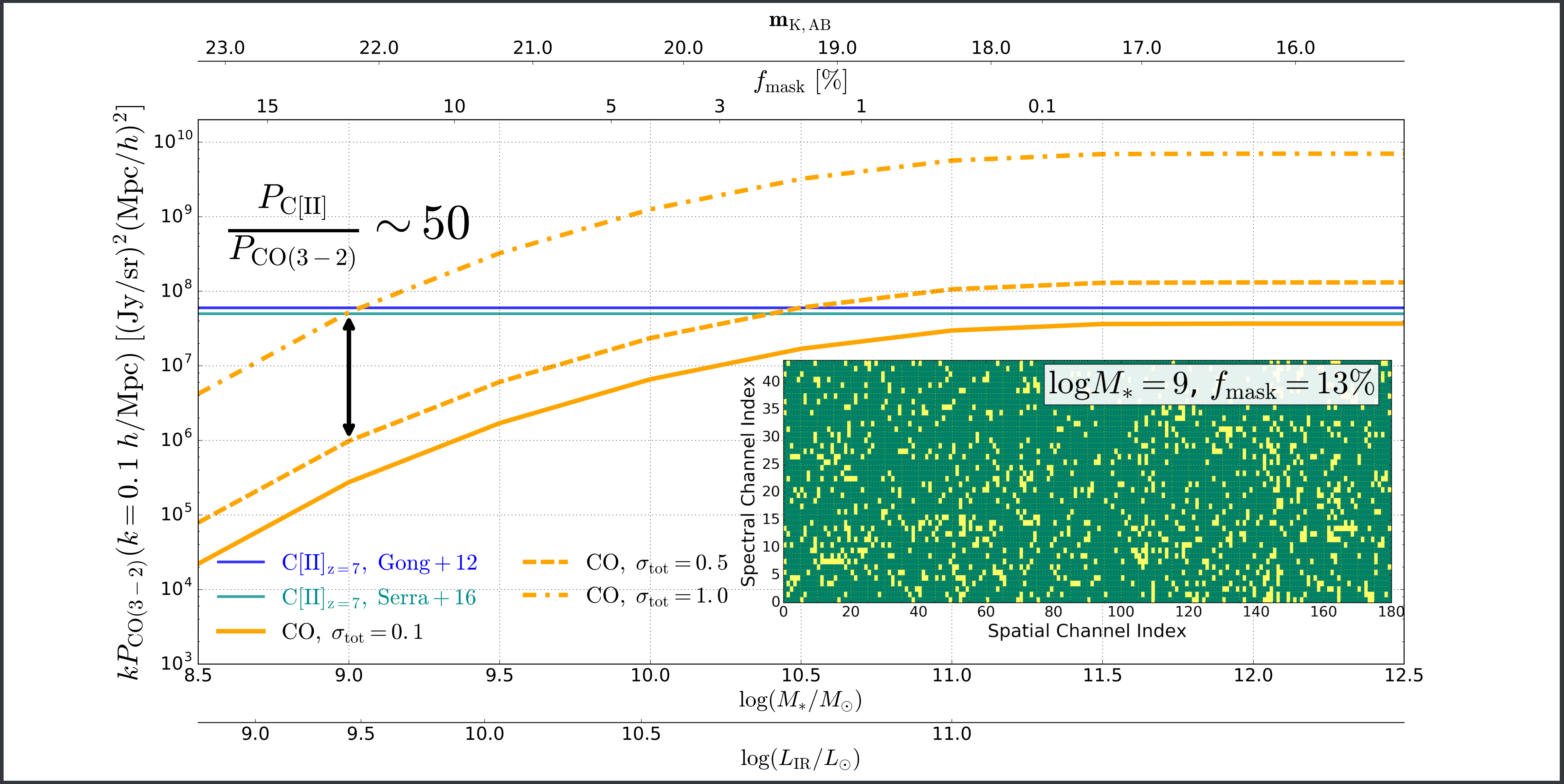
TIME collaboration (Sun et al., in prep)

- TIME will measure multiple CO J rotational transitions at 0.5 < z < 2
- Can be achieved via in-band cross-correlations of different J lines
- TIME will constrain the cosmic molecular hydrogen abundance across redshifts

Line de-confusion

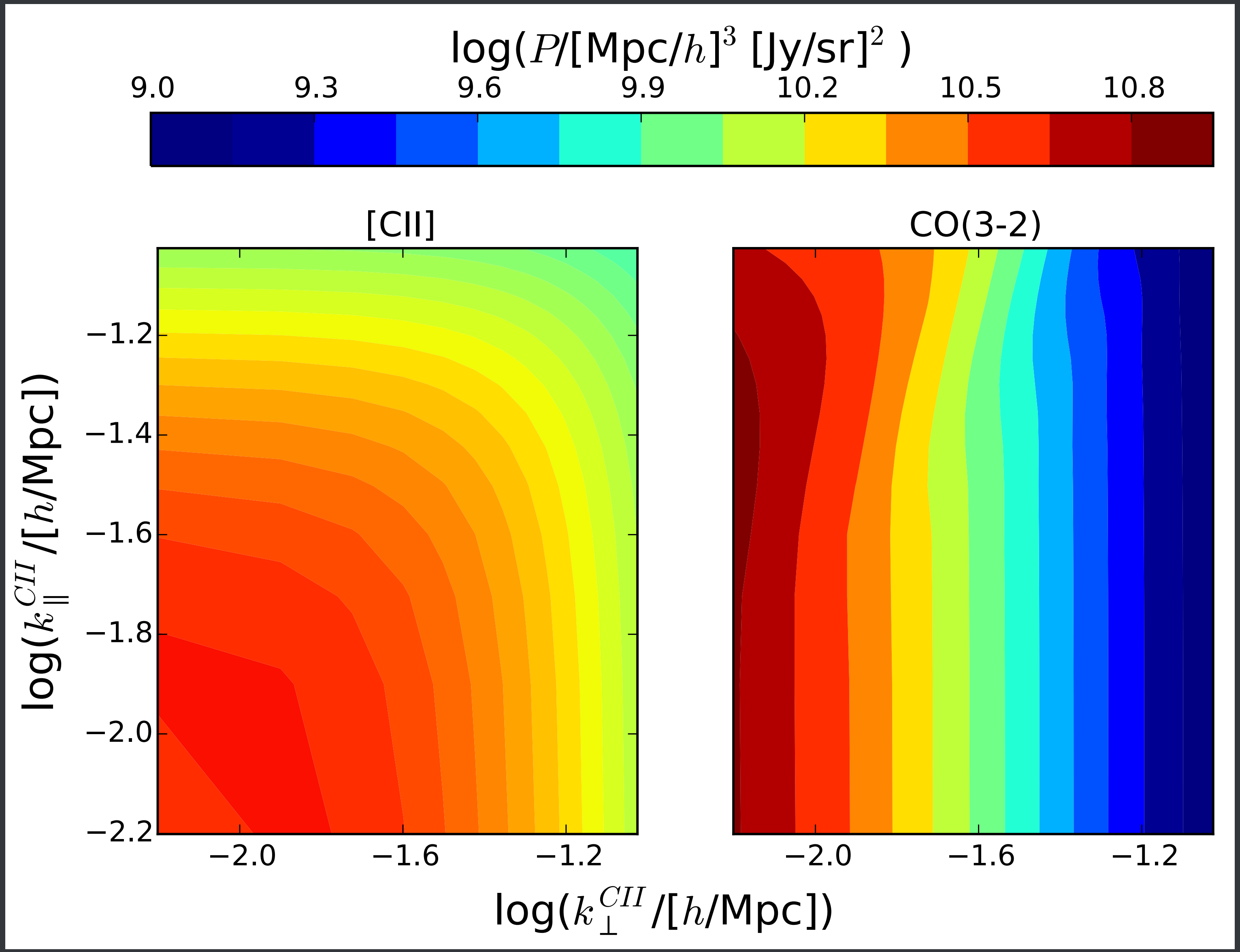
- High-z [CII] and low-z CO lines can be confused in TIME.
- We are planning to use a combination of well-demonstrated techniques:
  - Masking bright, low-z sources: employed in CMB, CIB, EBL and studied for IM (e.g., Sun+18, Silva+17).
  - Use the anisotropic power spectrum shape of [CII] and CO (from observing to comoving coordinates) to distinguish the lines (Visbal & Loeb 2010; Gong+14; Lidz & Taylor 2016; Cheng+ 2016).
  - Cross-correlations of different lines at same redshift (e.g., Visbal & Loeb 2010; Gong+12, +17).
  - Cross-correlations with galaxy tracers (e.g., Chang+10, Masui+13, Pullen+13, +18).

CO, [CII] signal de-confusion: source masking



TIME collaboration (Sun et al. 2018)

CO, [CII] signal de-confusion: Anisotropic power spectrum



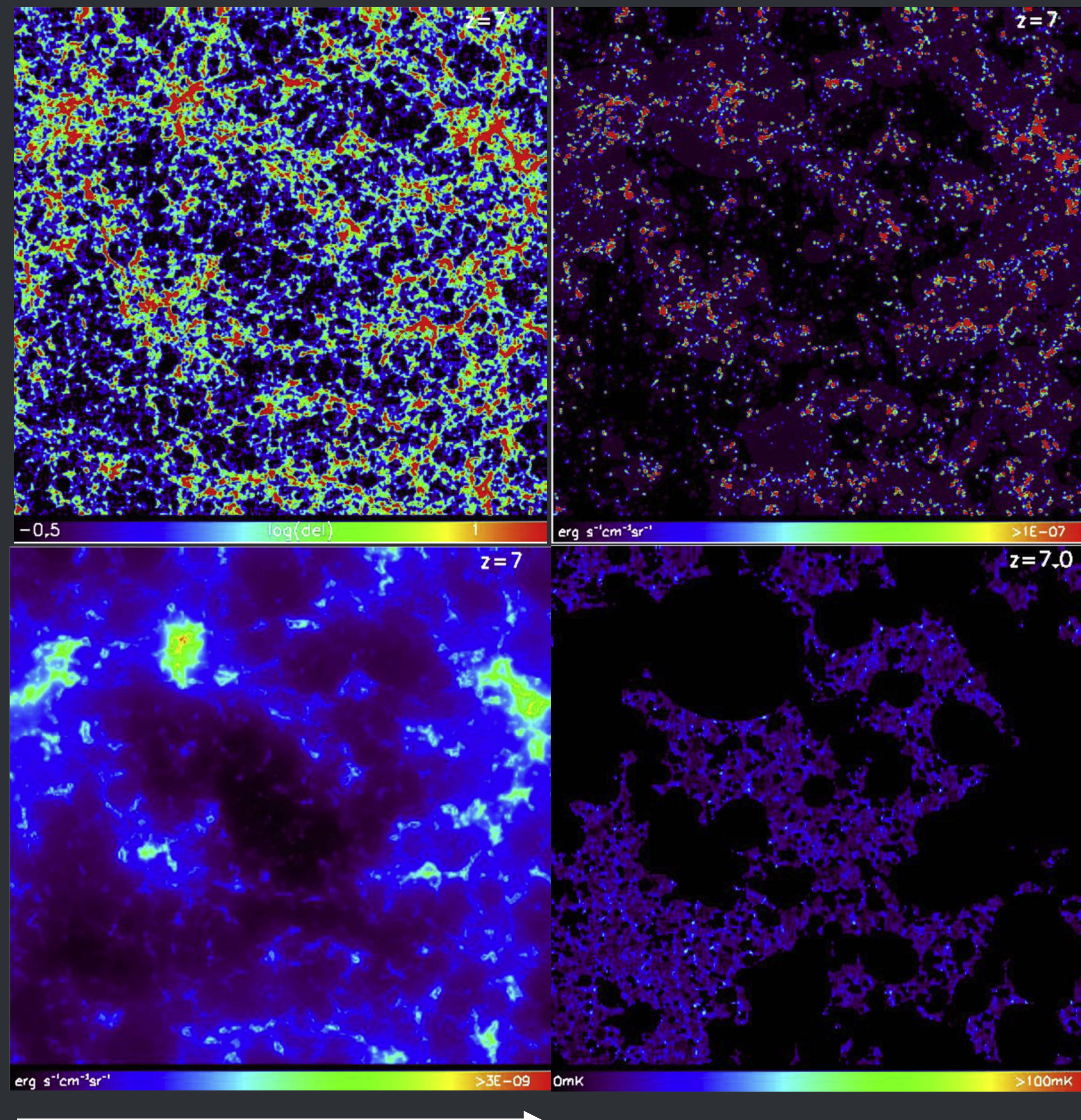
Cheng, Chang, et al. 2016

- High-z [CII] and low-z CO rotational lines can be confused in TIME
- Use the redshift-dependence of CO and [CII] from observing to comoving coordinates to distinguish the lines (Lidz & Taylor 2016; Cheng et al. 2016).

[CII], Lya, Ha, 21cm Intensity Mapping: large-scale, 3D EoR probes

Density fluctuation
z~7

Ionizing sources
(traced by Ha, [CII])



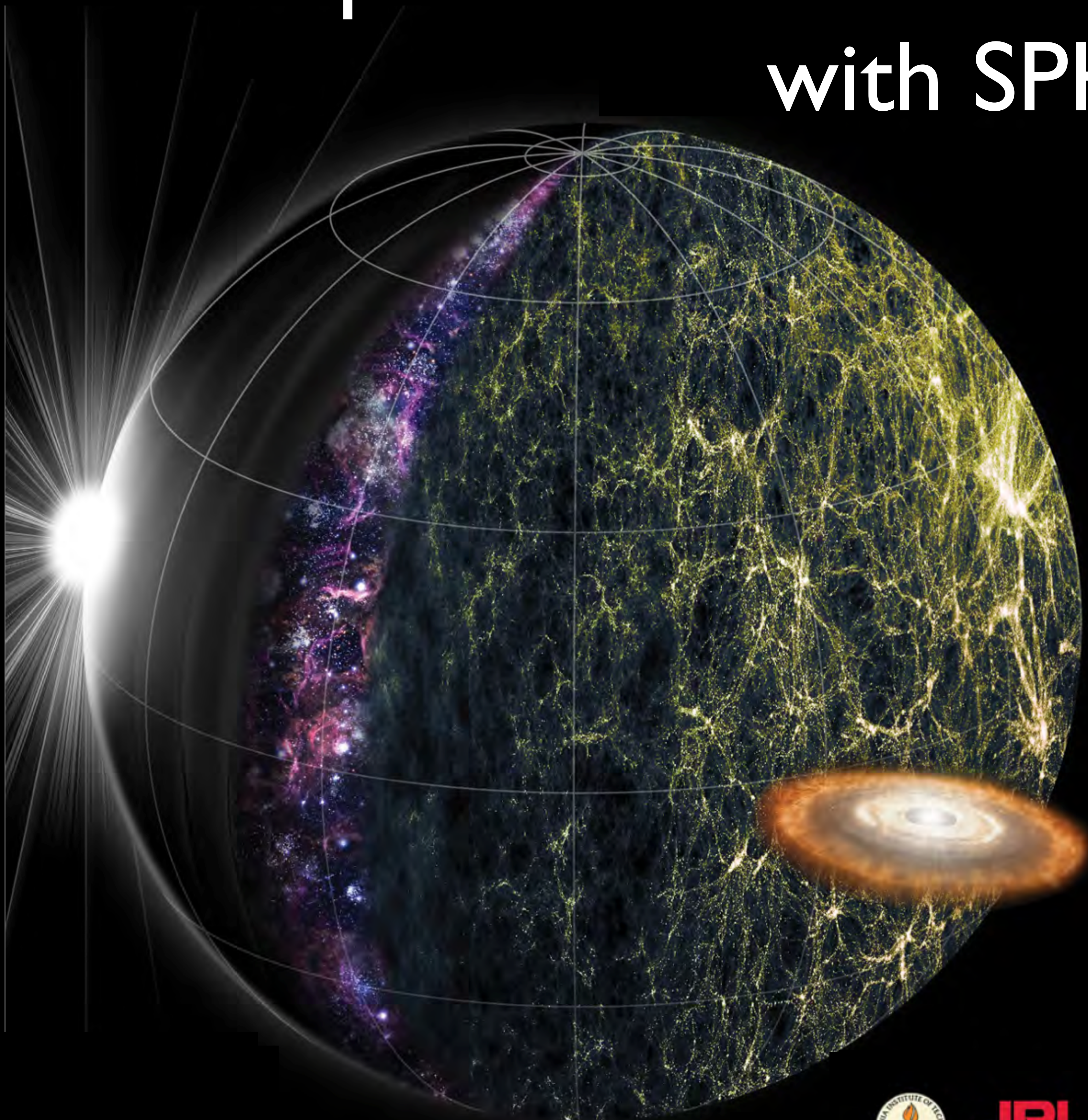
Ionized IGM
(traced by
scattering Lya,
[CII]?)

Neutral IGM
(traced by 21cm)

200 Mpc

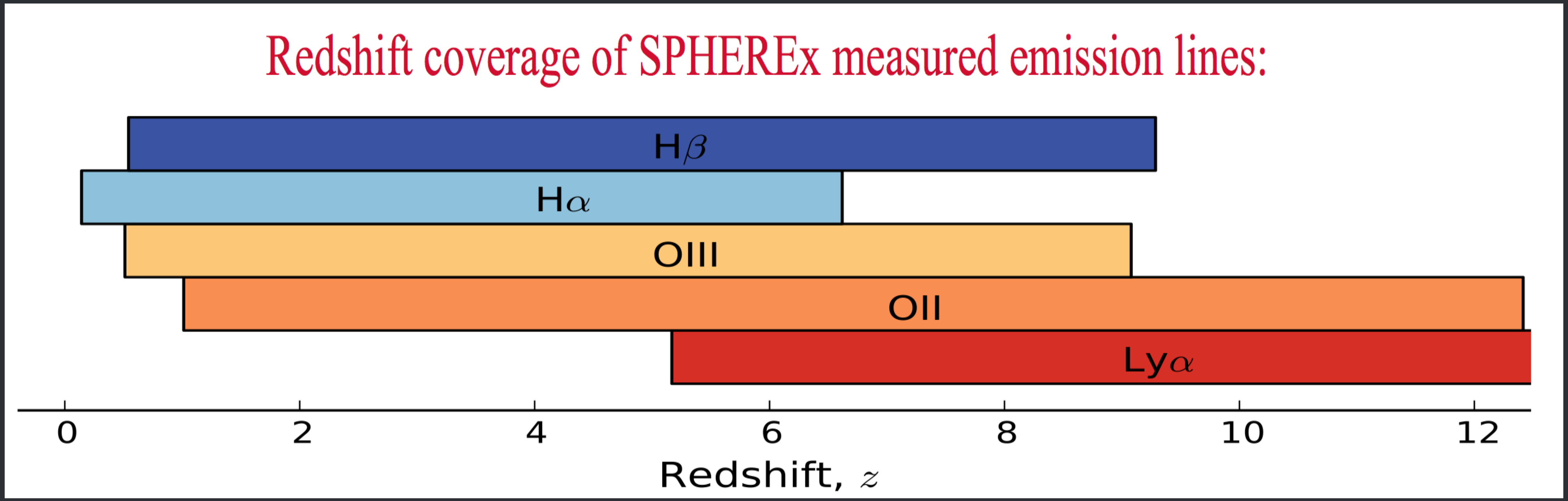
Heneka et al., 2017

Spectral Line Intensity Mapping with SPHEREx



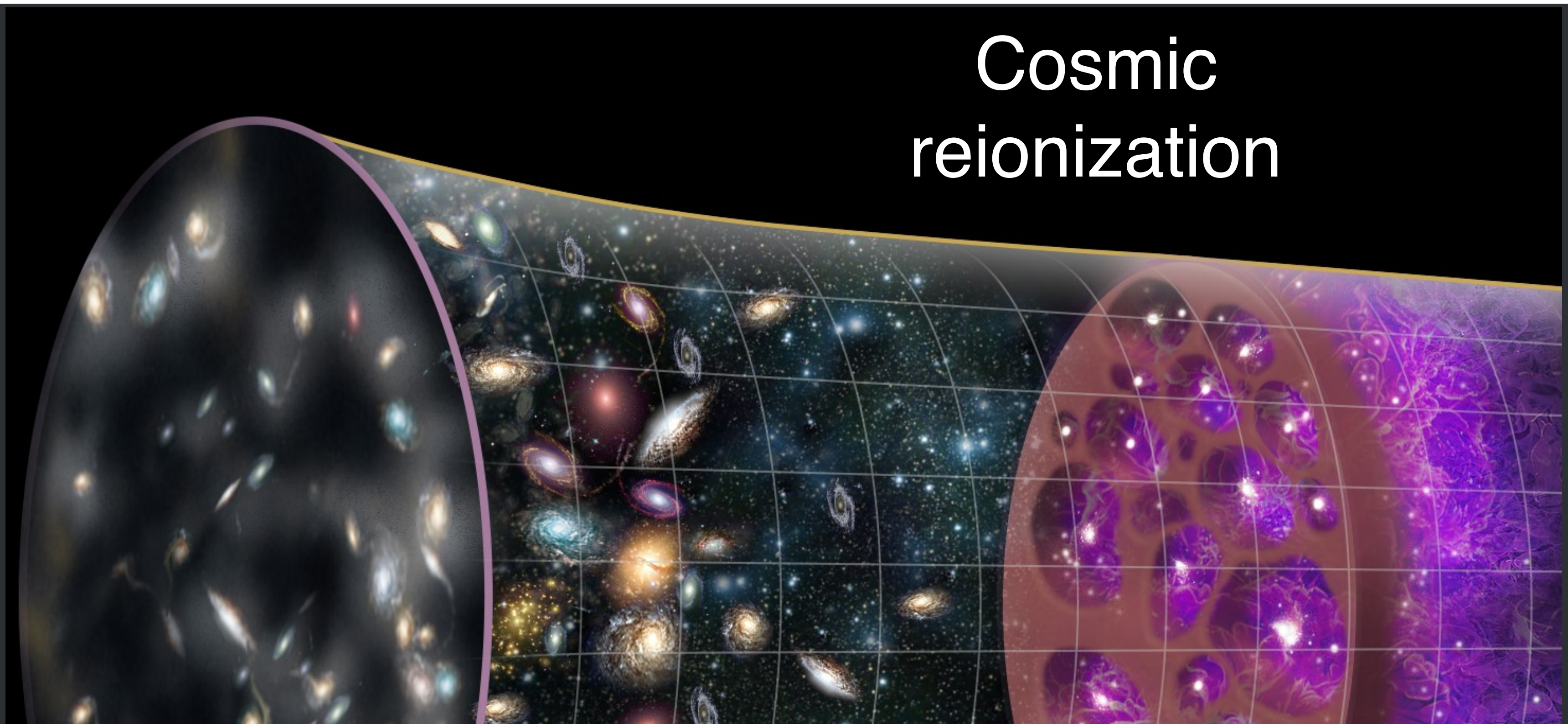
With
SPHEREx Science Team

SPHEREx deep fields:
Narrow-band Line Intensity Mapping



BAO expansion rate H(z)

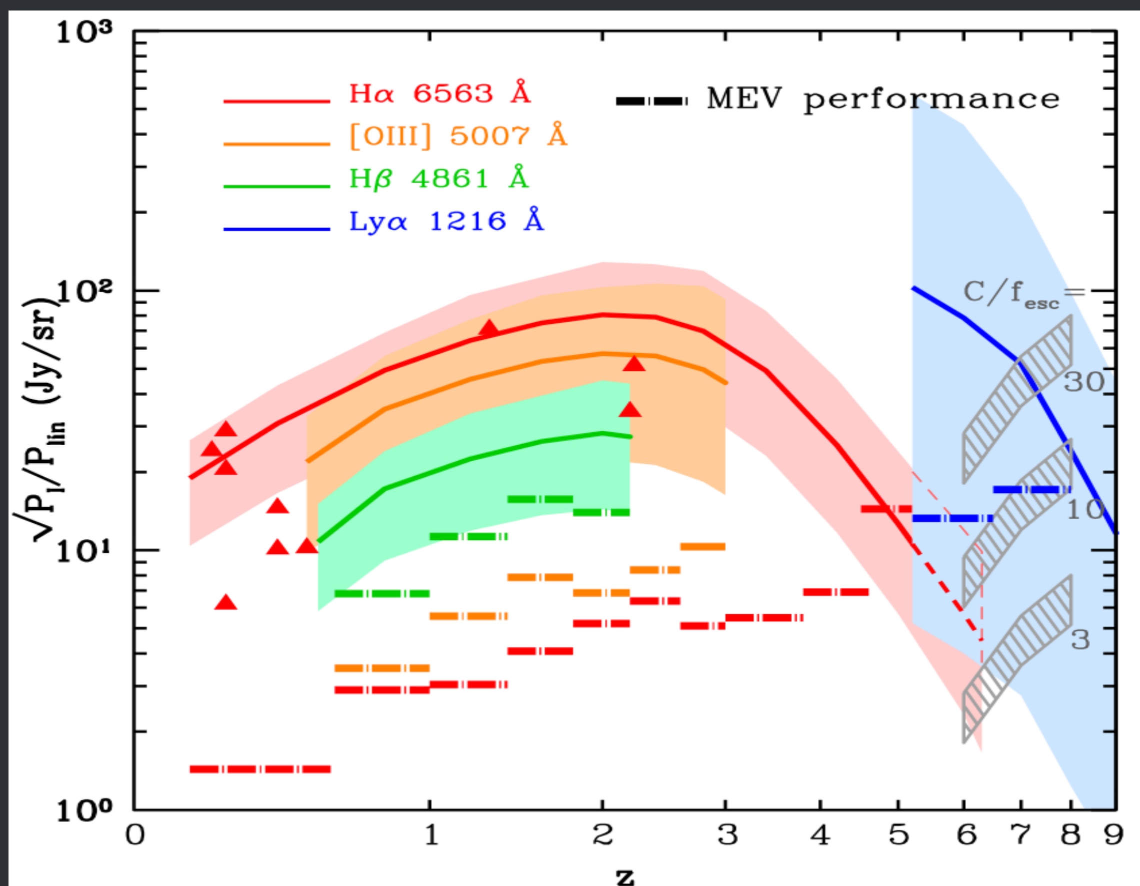
z



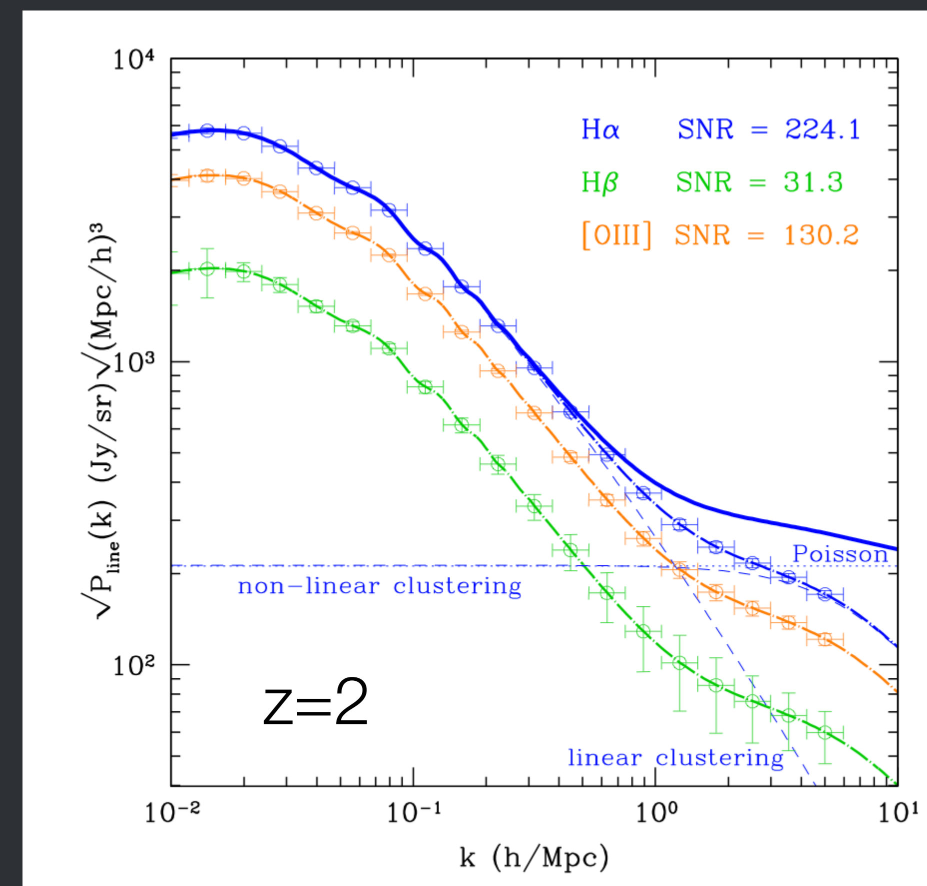
Line Intensity Mapping with SPHEREx

Fluctuations in Line Emission

Clustering amplitude (bias)



Power Spectra of Emission Lines



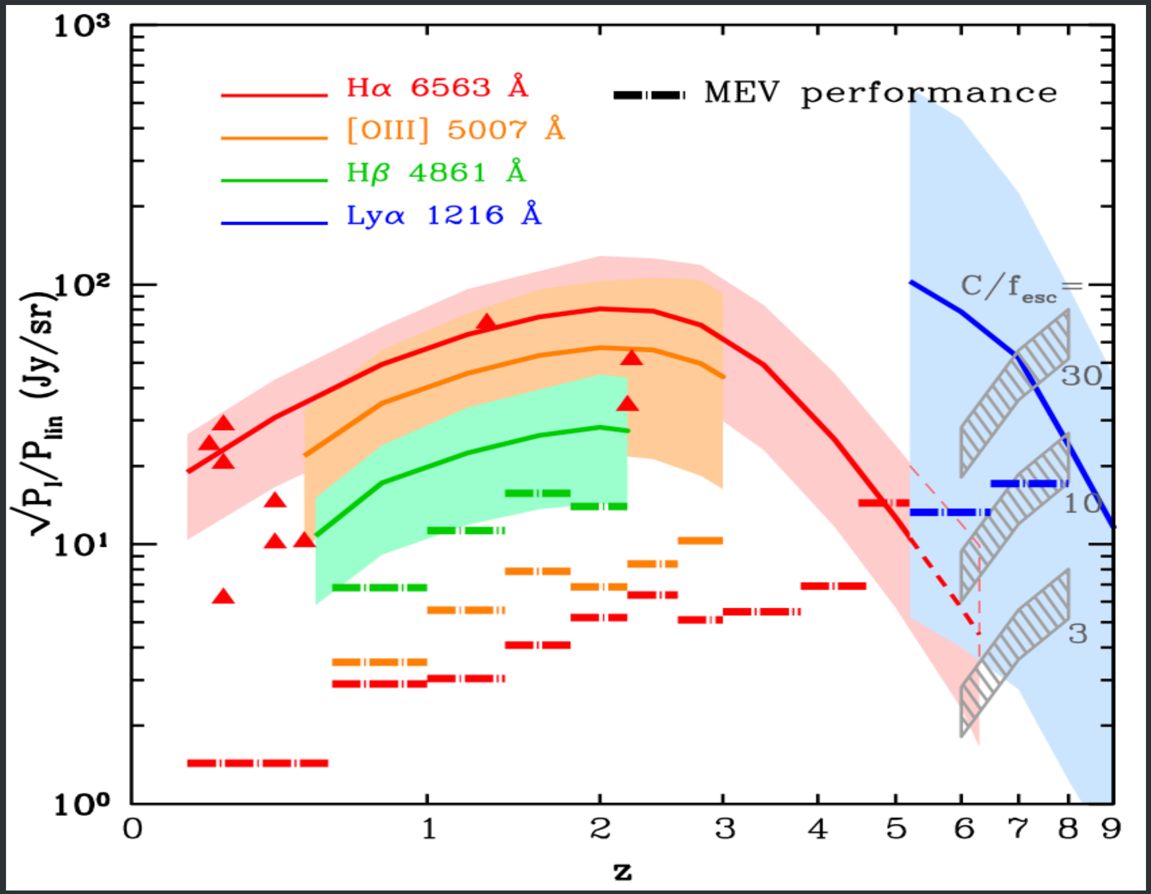
Doré et al., arXiv:1412.4872

- SPHEREx will measure statistically the fluctuations of multiple spectral lines associated with cosmic structures across redshift.
- SPHEREx will measure at high SNR the 3D clustering of multiple line tracers and the luminosity-weighted biases.

Line Intensity Mapping with SPHEREx

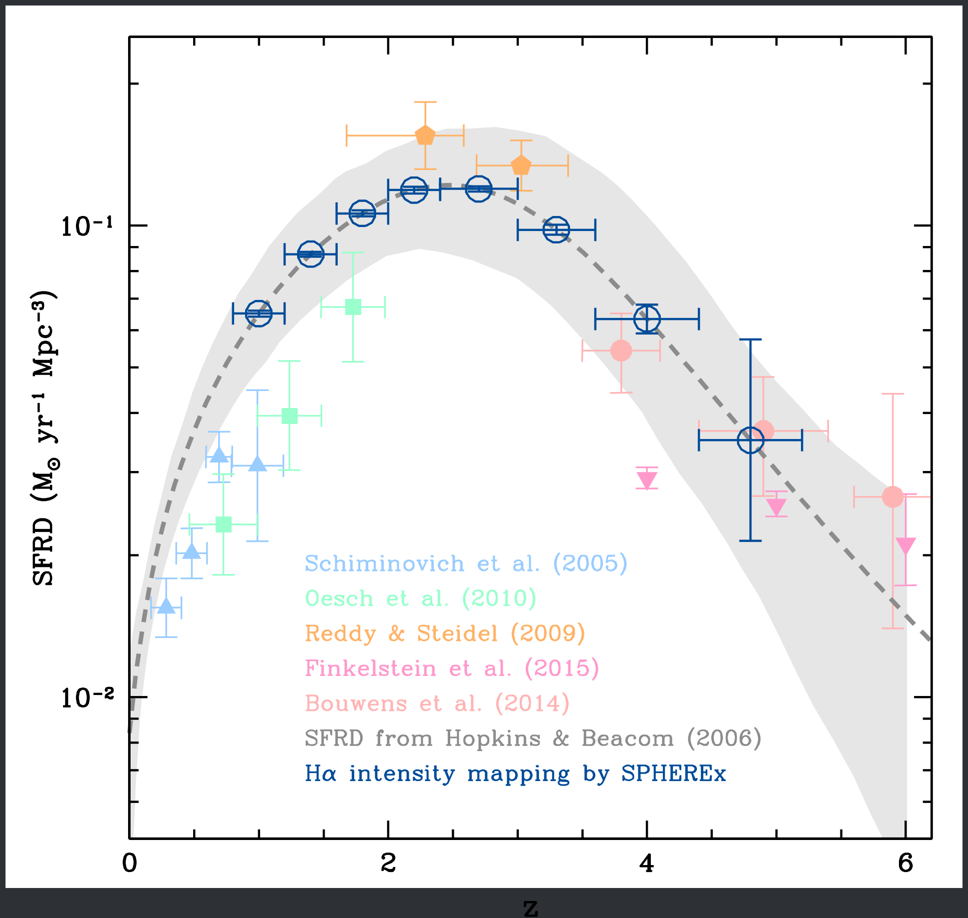
Clustering amplitude (bias)

Fluctuations in Line Emission



Doré et al., arXiv:1412.4872

SFRD from Hα intensity mapping

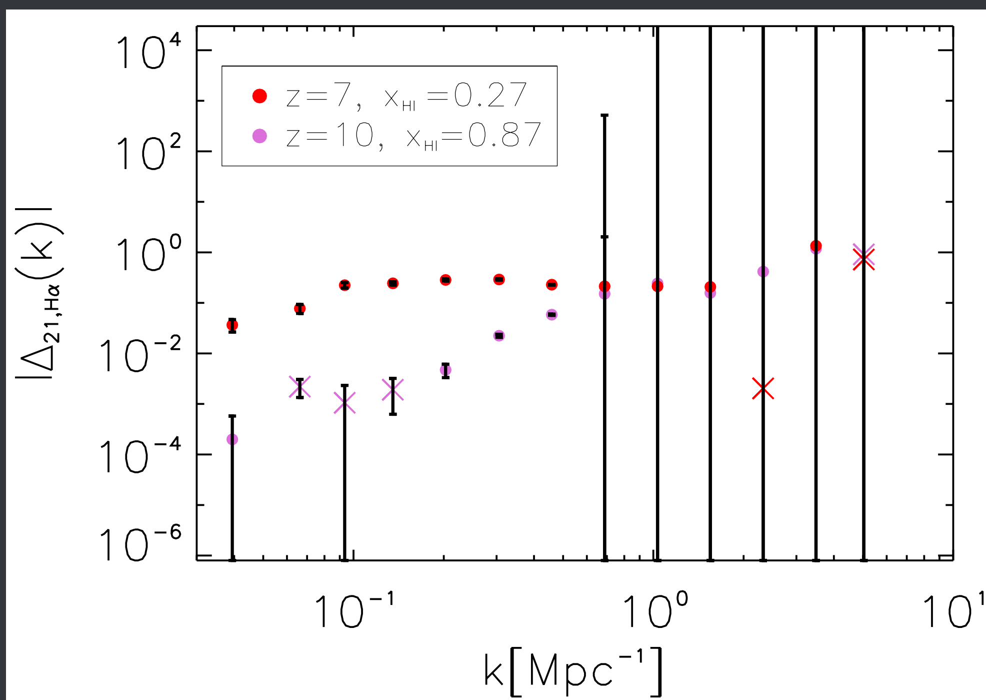


Gong et al. 2017

- SPHEREx will map SFR through cosmic time up to z~5 via Hα Intensity Mapping.
- SPHEREx has the sensitivity to detect Lyα from EoR, inferring ionizing photon production.

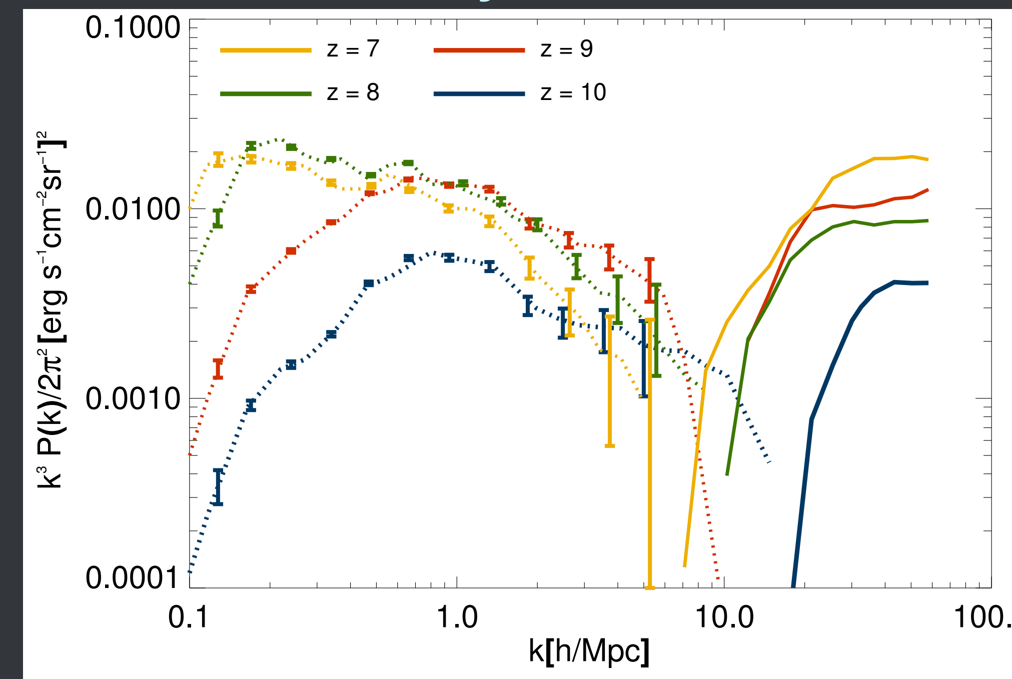
21cm, Ha, Lya cross-correlations

Ha x 21cm



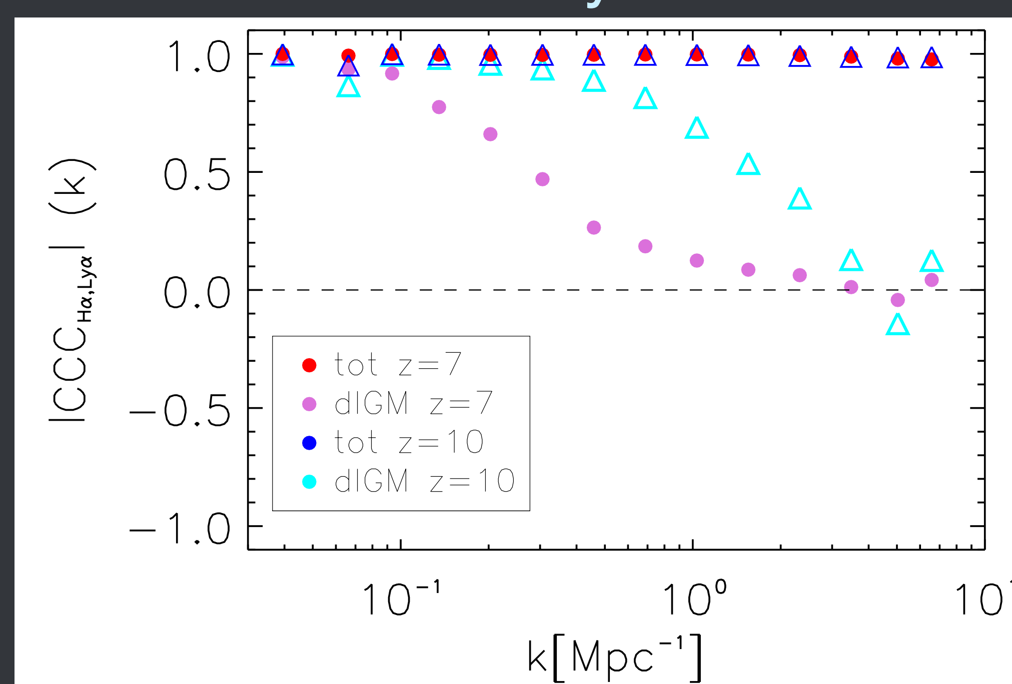
Heneka+ in prep

Lya x 21cm



Chang+ 15

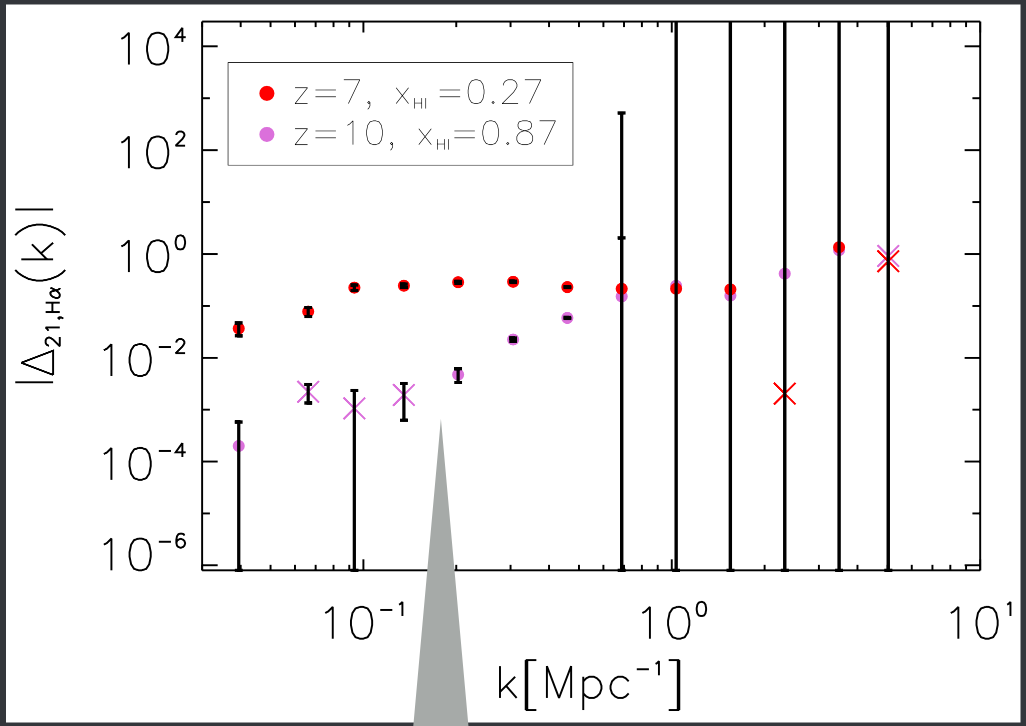
Ha x Lya



Heneka+ 17

21cm, Ha, Lya cross-correlations

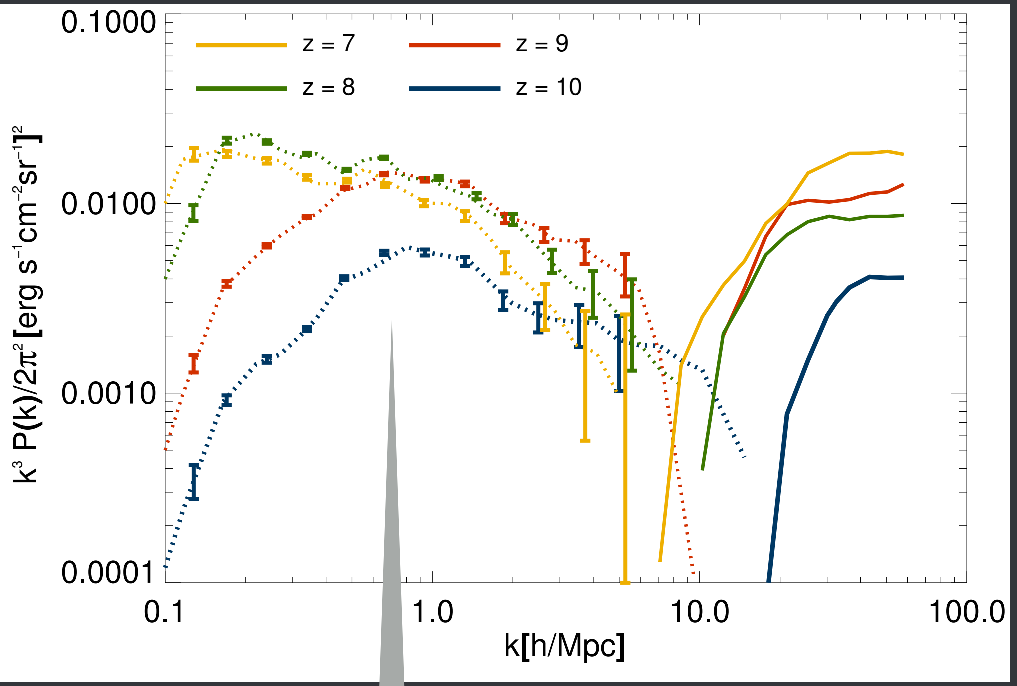
Ha x 21cm



Heneka+ in prep

Anti-correlated on bubble scales

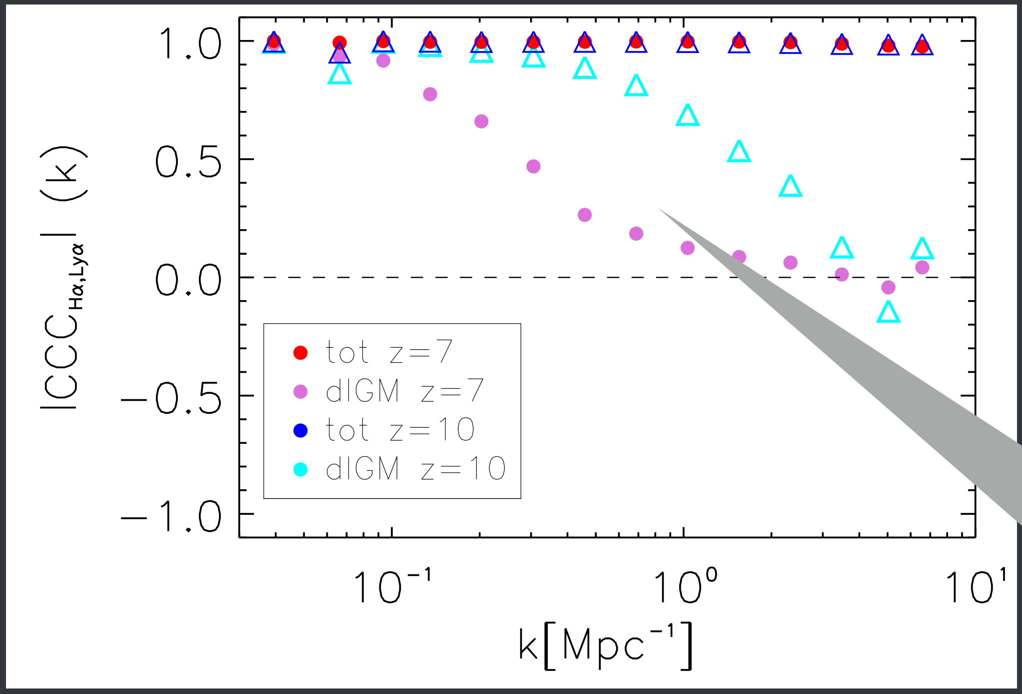
Lya x 21cm



Chang+ 15

Anti-correlated on bubble scales

Ha x Lya

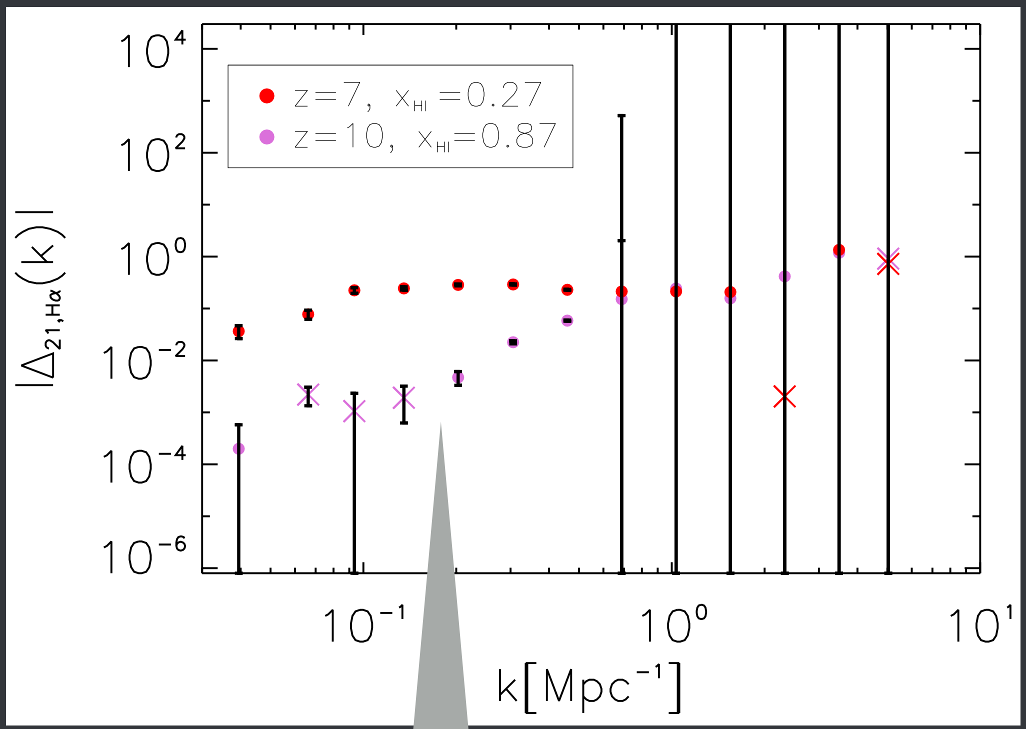


Heneka+ in prep.

Tracing diffuse IGM Lya

21cm, Ha, Lya cross-correlations

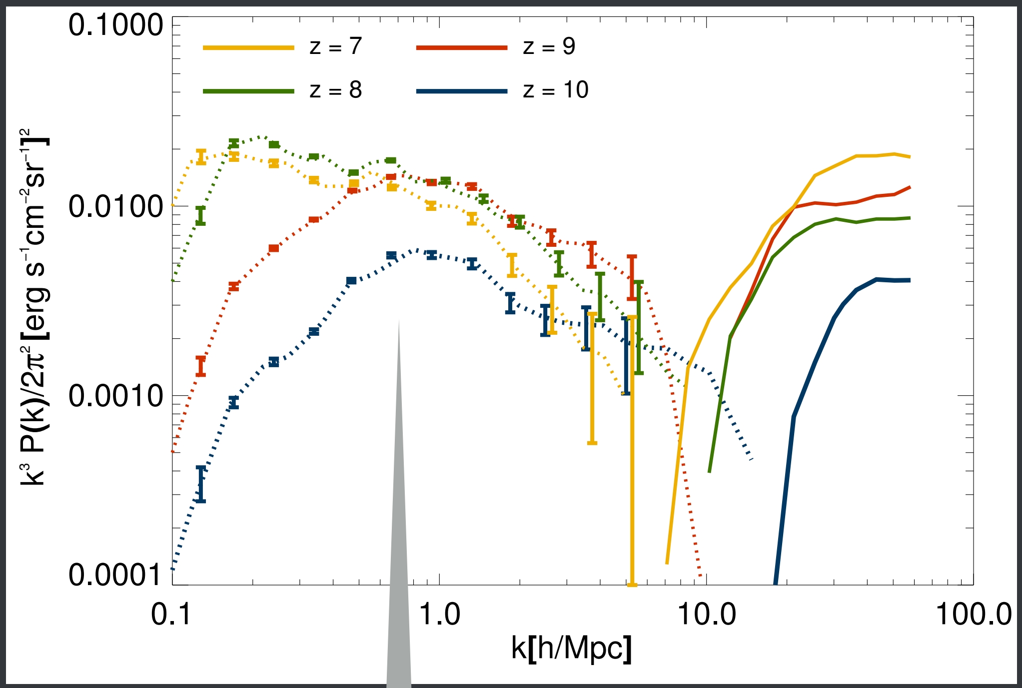
Ha x 21cm



Heneka+ in prep

Anti-correlated on bubble scales

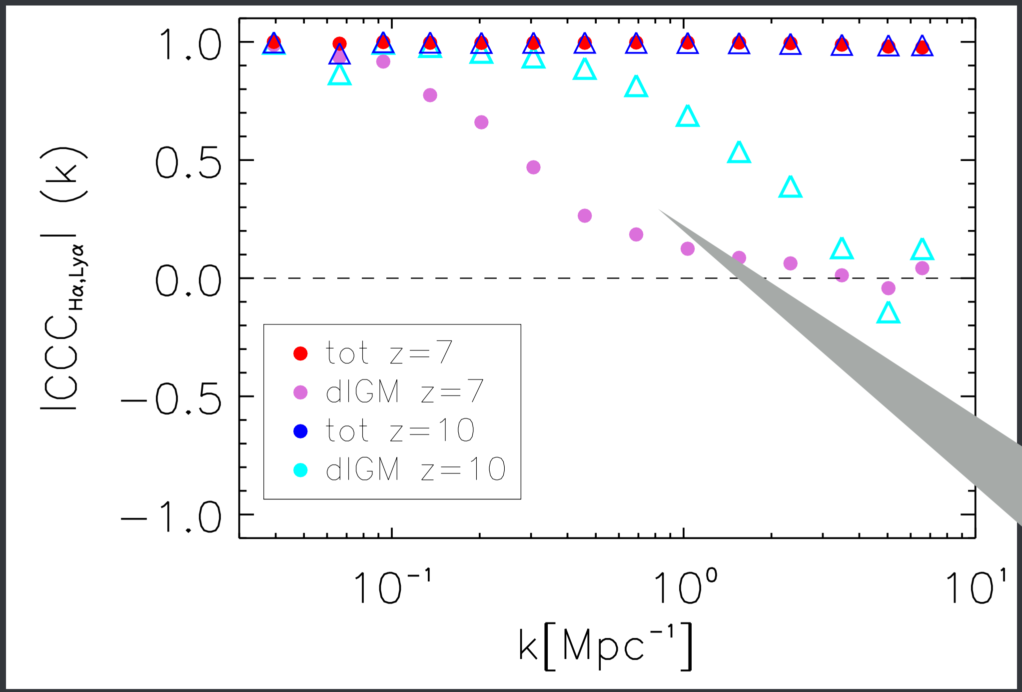
Lya x 21cm



Chang+ 15

Anti-correlated on bubble scales

Ha x Lya

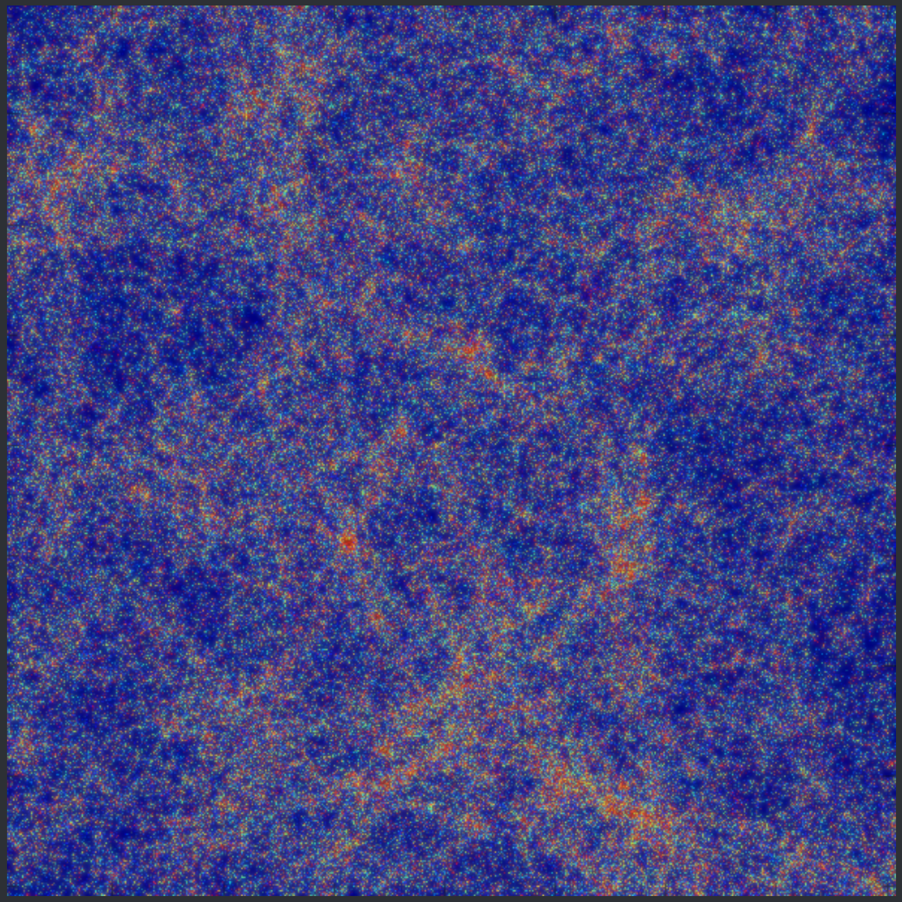


Heneka+ in prep.

Tracing diffuse IGM Lya

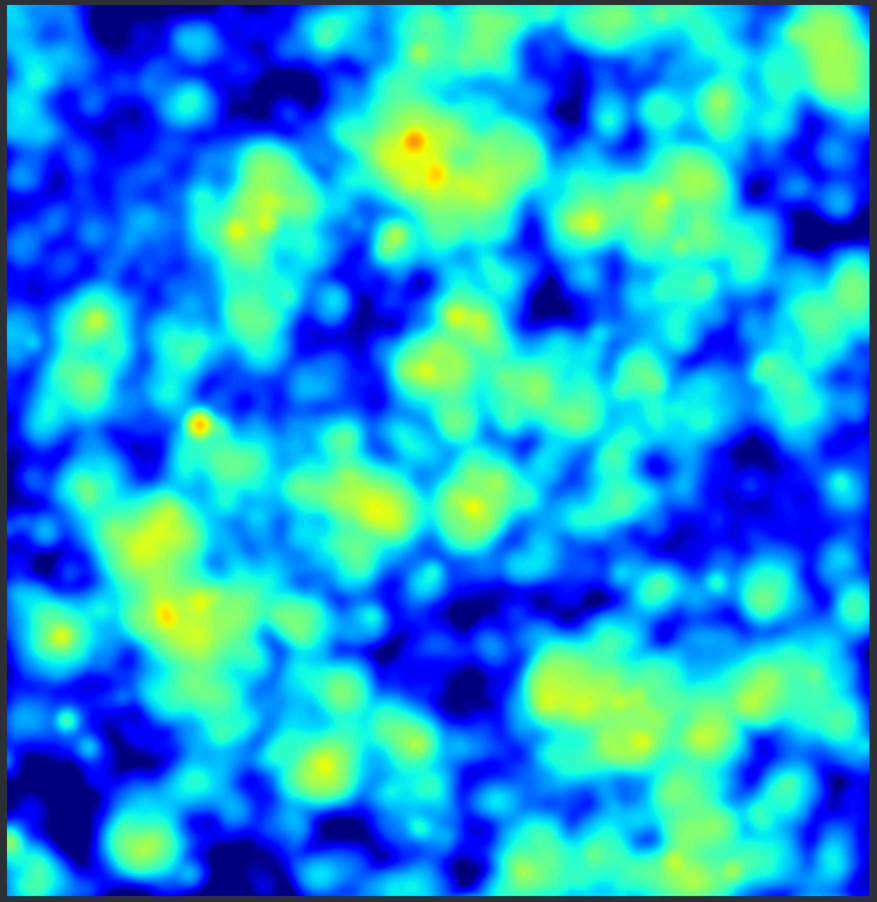
Line Intensity Mapping with SPHEREx

Hα fluctuations at z~1



50 Mpc

Lyα fluctuations at z=6.6

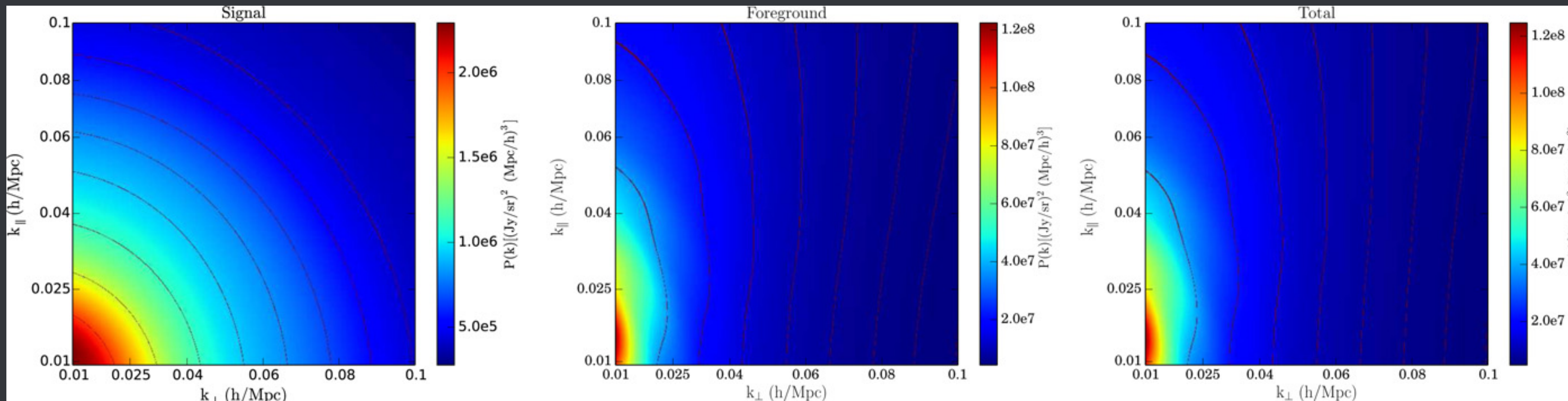


50 Mpc

- SPHEREx will produce 96 spectral images and map 3D intensity fluctuations of multiple line tracers across redshift.
- Simulation work on-going, including a 10 deg^2 lightcone of multiple emission lines (Hα, Hβ, [OIII], [OII]) at $1 < z < 10$ plus stellar continuum using the Hidden Valley simulations, and Lyα analytical treatment of radiative transfer effects during EoR.

Line signal de-confusion

Lyα at z~7 | Hα at z~0.5 | Lyα + Hα



Gong+ 14

- High-z Lyα and low-z Hα lines can be confused in SPHEREx in the IM regime.
- We are planning to use a combination of well-demonstrated techniques:
    - Masking bright, low-z sources: employed in CMB, CIB, EBL and studied for IM (e.g., Sun+16, Silva+17).
    - Use the anisotropic power spectrum shape of Lyα and Hα (from observing to comoving coordinates) to distinguish the lines (Visbal & Loeb 2010; Gong+14; Lidz & Taylor 2016; Cheng+ 2016).
    - Cross-correlations of different lines at same redshift (e.g., Visbal & Loeb 2010; Gong+12, +17).
    - Cross-correlations with galaxy tracers (e.g., Chang+10, Masui+13, Pullen+13, +17).